4

Illustrated World of Science Encyclopedia

Earth Science I:
THE EMERGING
EARTH

THE WORLD OF SCIENCE

THE WORLD OF SCIENCE

VOLUME

4

EARTH SCIENCE I

The Emerging Earth

with

The Illustrated Science Dictionary

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CHICAGO

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VOLUME 4

EARTH SCIENCE I

The Emerging Earth

INTRODUCTION

This volume emphasizes the physical makeup of the Earth on which man lives. Although the book is not rigidly divided into fixed chapters, three distinct areas of interest are developed. First, the basic properties of such large-scale features as the Earth's core and mantle are examined.

Following the introductory articles on the origin of earthly materials and life, the scientist attempts to answer such difficult—and intriguing—questions as: How much does the Earth weigh? What is the source of terrestrial heat and how hot is the Earth thousands of kilometers below its surface? What causes earthquakes and mountain building? Is it true, as suggested by the theory of isostasy, that the continents float on the underlying mantle, much as a cork bobs up and down on water?

Among the newest ideas discussed in this first area of interest is the theory of continental drift and sea floor spreading. Scientists suggest that new sea floor is being created daily from material originating deep within the Earth's mantle. This newly created sea floor, along with large-scale convection currents within the mantle, may be instrumental in moving vast continents measurable distances. Such theories of mantle and core behavior cannot stand alone, however; they must fit into a cohesive picture of the Earth as a whole. Accordingly, the second area of interest critically reviews and examines the forces and properties of the Earth's crust.

Perhaps the most dramatic display of crustal forces are the spectacular eruptions associated with worldwide volcanic activity. The interested reader will discover not only how volcanic cones are formed, but also the tragic effects of a volcanic eruption at Pompeii. Materials spewed from volcanic cones form diverse rock types, and the nature and forms of these rocks are discussed and explained. In many regions, magma spills out onto the surface of the Earth, forming vast basaltic plateaus. In other places the magma solidifies as batholithic masses just beneath the Earth's surface; these masses are invisible to the layman, but are carefully studied and classified by geologists as either concordant or discordant intrusions.

Anyone who has marveled at the grandeur of such mountains as the Rockies, the Himalayas, and the Alps is surely aware that vast forces are present in the Earth's crust. Additional articles discuss how rocks are folded and broken and outline the careful classification of these phenomena. The question of why certain areas of the world are characterized by volcanic and mountain-building activity is also considered.

The third area of interest emphasizes the visible surface of the Earth. What, for example, shapes the valleys and hills found throughout America, the mountains of the east and west coasts, the plains of the interior United States? Surprisingly, perhaps, more than just the errosive power of water is involved in forming the land surface. A comprehensive presentation of erosion discusses the relentless effect of wind over the centuries, the subtle but continuing effect of chemical reactions, and the grinding power of glaciers in the distant past.

The effect of water, however, plays a dominant role in geologic processes and a succession of articles deals with the evolution and life cycles of rivers and lakes. The oceans, covering three fourths of the Earth, also occupy a prominent part in these discussions. Surprisingly, the action of water does more than wear away and destroy surface features; water also plays a vital role in depositing new rocks to replace the old.

Finally, the problem of determining the age of a rock is explored. Most geologists agree that thorough understanding of geologic time is pertinent to an understanding of Earth history. Such an important subject is an appropriate ending to a volume dedicated to a study of the materials and the geologic processes involved in the past and present.

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THE ORIGINS OF EARTHLY MATTER | subsequent changes in time

← **MATTER IN THE UNIVERSE**—Most of the matter in the universe is found in nebulas, great collections of atoms, gas, and cosmic dust.

To a person walking through the countryside or strolling through a mountain valley, the landscape seems still and unchanging, creating the impression that it has always been the same and always will be. However, this is a superficial impression and a closer examination reveals precisely how superficial it is.

THE EVER-CHANGING EARTH

A large river, for example, may be observed to flow slowly and peacefully across a plain. Close examination shows that the shallow water running slowly past the banks is carrying grains of sand and soil with it. The water rolls the sand along, lifting it from the bottom and depositing it farther downstream. The river may be compared with a huge machine designed for the transportation of materials. All rivers carry enormous quantities of gravel, sand, and mud toward their mouths. Every year, millions and millions of tons of detritus (the products of erosion) are transported by rivers to the sea. Even the mountains testify to the truth of this statement. Rivers carve out of their banks the matter that they carry to the sea. The volume of empty space in a valley is equal to the amount of rocky material that the rivers have transported to the ocean. A mountain range would be a high, flat plain without valleys except for the erosion produced by running water, glaciers, and wind.

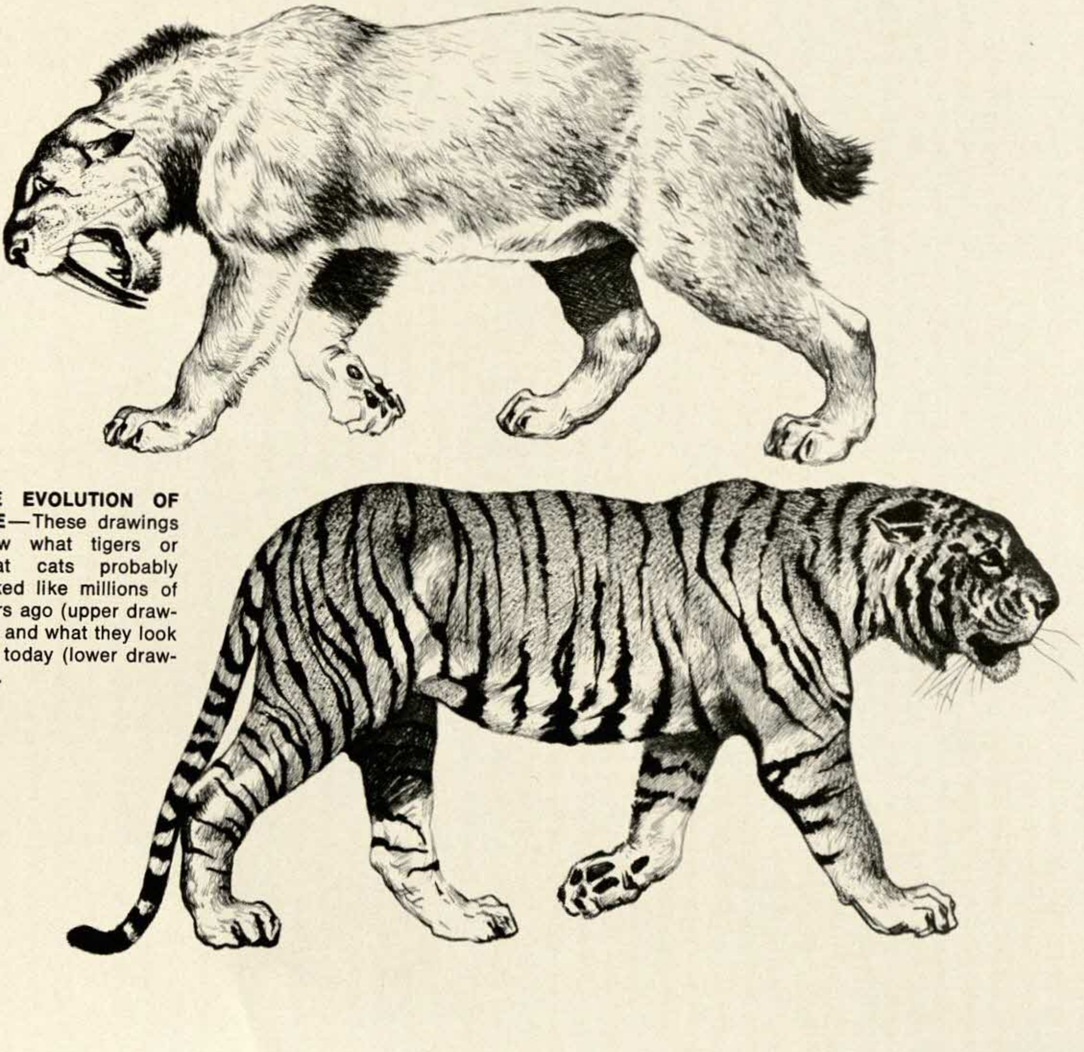
The entire surface of the Earth displays the signs of its continual transformation. The area around a volcano is replete with traces of lava and other materials erupted onto the surface at some time in the past. The study of ancient history reveals that many European cities built by the Romans on the seashore are now located on dry land far from the water. These are obvious examples, but they indicate the extent of change undergone by the land over a period of a relatively few years. Imagine how different the Earth must have appeared several million years ago!

CONTINUING CHANGES IN LIFE-FORMS

Living organisms change and evolve even more rapidly than does the Earth on which they live. The tigers and elephants that lived in Europe in prehistoric times were quite different from the tigers and elephants living today. They were much larger and more elaborately equipped with tusks and teeth. If the reader were able to travel backward in time a hundred million years, he would scarcely recognize any of the animals that he might encounter. If he were to be transported back into even more remote periods, he would find neither animal nor plant life. Before that, not even the Earth existed. The matter of which the Earth is made was scattered in space in the form of very rarefied gas. Here begins the story of the Earth.

THE MATTER OF THE EARTH

There was a time, very long ago, when neither the Earth nor the sun existed. How long ago? No one knows for sure,



THE EVOLUTION OF LIFE—These drawings show what tigers or great cats probably looked like millions of years ago (upper drawing) and what they look like today (lower drawing).

but only recently, scientists have calculated that the Earth was formed about five billion years ago. This is a most imprecise date. It is entirely possible that studies presently in progress will conclude that the Earth originated at a more recent date, or perhaps one that is even more remote.

Regardless of the exact date, the solar system was formed and the Earth came into being a very long time ago. But how did all this take place? It is believed that matter, spread throughout space, began to coalesce. This matter then became divided into fragments, some large and some small. The largest fragment formed the sun. The smaller fragments constituted the planets and the smaller celestial bodies that began to revolve around the sun. But where did all this matter come from? The situation in the rest of the universe at the time of the Earth's formation is not known, nor is the history of the universe prior to the formation of the solar system. Probably all matter that now makes up the solar system was spread out through space in a gaseous form. Scattered in that almost limitless space, it certainly must have been very rarefied, probably resembling the nebulas (masses of gaseous cosmic matter) known to astronomers today. To express in tons the amount of matter contained in the sun, in the Earth, or in a galaxy, a huge number with a long series of zeroes would be necessary. However, the space that separates celestial bodies from one another is so vast that the total amount of matter in the universe may be considered as small, or even exceedingly small. If all the atoms in the universe were distributed evenly throughout space, as perhaps they were at one time, a gram of matter would occupy every 100,000 cubic kilometers of space. A volume of these dimensions would hold 500 objects the size of the Earth.

THE TRIANGLE GALAXY—The spiral form of this galaxy is due to the fact that stars close to the center revolve more rapidly than those farther away. This kind of formation is characteristic of certain kinds of nebulas early in their history.

THE GREAT ANDROMEDA GALAXY—Matter in the center of this galaxy has revolved many times around its center of gravity, and the stars have become rather evenly distributed. Dull stars are found in the Andromeda Galaxy, indicating that this island universe is older than the Triangle Galaxy—indeed, Andromeda is almost the same age as the Milky Way, the galaxy to which our solar system belongs. The distance of Andromeda from the solar system has been estimated at about 2 million light-years; it can be seen with the naked eye.

RAREFIED MATTER

Matter is, therefore, so rare that the universe may be described as empty. No man-made vacuum pump is capable of producing a vacuum as complete as the cosmic vacuum. Even when a vacuum is created within a container, using the most efficient vacuum pump available, a little air remains. This remaining air may amount to about 100,000 molecules per square centimeter. Were the matter in outer space evenly distributed, it would be so rarefied that a cubic centimeter would contain only a few molecules. A physicist who was able to study such a vacuum would experience great difficulty, even using the most precise instruments, in detecting any matter at all. He would never find enough molecules together to be able to perceive their existence.

In the condensed matter that comprises the sun, the Earth, the planets, and other bodies in the solar system, atoms may be said to stand shoulder to shoulder. However, in the rarefied matter that exists between stars, an atom moving like a projectile in a straight line would encounter another atom only once every 100 billion kilometers. Hundreds of millions of galaxies are scattered throughout a sphere whose radius is estimated in billions of light-years.

THE PAST AND FUTURE AS SEEN IN OTHER GALAXIES

The sun is one of countless billions of stars comprising the Milky Way Galaxy. From the Earth, many other galaxies may be observed; these gigantic collections of celestial bodies are all separate. All

THE ANDROMEDA SATELLITE—The spiral form of the Andromeda Satellite has disappeared, and the stars that make up this galaxy are billions of years old. The Andromeda Satellite has had time enough to lose all traces of its original spiral formation.

of the galaxies lie at enormous distances from the Earth's galaxy, the Milky Way—but to an earthbound observer, these galaxies resemble individual stars, clusters of stars, or clouds in the distant heavens.

Three of the important galaxies are the Triangle Galaxy (the spiral nebula in Triangulum, identified by astronomers as M 33), the Great Andromeda Galaxy (M 31), and one of the two satellite galaxies of Andromeda. According to some theories, each of these three galaxies was created at a different time, and each resembles the Milky Way as it once was or as it will be in the future.

The Triangle Galaxy is the youngest of the three. Its matter has condensed into long armlike formations that give the galaxy a spiral shape. In the solar system, the planets farthest from the sun revolve more slowly than those that are closer. Likewise, within a galaxy, the stars that are farthest from the center move more slowly than those in the center. Thus the matter, initially distributed in a random fashion, in time assumes a spiral formation. Astronomers calculate that a galaxy such as the Triangle Galaxy has been rotating for only about a billion years or perhaps even less; it therefore can be considered young.

The arms of Andromeda, on the other hand, are spiraled tightly around the center. On the basis of various theories, astronomers conclude that the Andromeda Galaxy is older than the Triangle. The central part of the Andromeda Galaxy has had sufficient time to make a great number of revolutions around its center, and the celestial bodies are more evenly distributed than those in the Triangle. Stars in the Andromeda Galaxy are rather dull and, therefore, somewhat older than those in the Triangle.

Finally, the galaxy which is called the Andromeda Satellite (because of its closeness to the Andromeda Galaxy) shows no trace of spiral arms. Its stars are of the type that astronomers believe to be many billions of years old. This galaxy is very old and has had enough time to lose all traces of its original spiral formation.

When the sun and the Earth came into existence, the "island universe" in which they move had an appearance probably very similar to that of the Triangle Galaxy. If the Milky Way could be observed today from a suitable distance, it undoubtedly would resemble the Andromeda Galaxy. In the future, it probably will take on the shape of the Andromeda Satellite, although it will be larger.

THE EARTH WITHOUT LIFE

early developments in the lithosphere and atmosphere

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A STRIP MINE—Fossil fuels such as coal are indirectly derived from the atmosphere because they were formed from plants that absorbed carbon dioxide from the air many millions of years ago; the plants transformed the carbon dioxide by photosynthesis.

these elements from the atmosphere is simple in concept, but somewhat difficult in practice. Air is first liquefied and then distilled. Just as alcohol is obtained by the distillation of wine (which is made up of water, alcohol, and aromatic substances), all the aforementioned gases can be distilled from liquid air. Obviously, to collect the rarer gases, enormous quantities of air must be distilled.

Helium merits particular attention. The helium atoms found in the atmosphere remain for only a short period of time before escaping into space. These atoms are very light and move at very high speeds, even at low temperatures; those that make their way into the upper atmosphere are easily dispersed into space. The slower helium atoms can be accelerated by collisions with atoms of other gases; as a consequence, all the helium in the atmosphere is in the process of being lost.

How can helium still be discovered in the air? Helium is being continually produced, because radioactive substances present in rocks (uranium and thorium among the more important) give off alpha particles as they disintegrate. These particles are actually the nuclei of helium atoms. Sooner or later, the helium produced by radioactivity in the rocks makes its way to the surface of the Earth and eventually escapes from the atmosphere. To know how much helium the Earth produces and loses through the atmosphere annually, it would be necessary to know how much uranium and thorium exist in the Earth's crust. Of course, not all the helium manages to reach the surface of the Earth; some of it is trapped below ground.

If the atmosphere had not lost its helium and if this gas had continued to collect over millions of years, the gaseous envelope surrounding the Earth today would contain more helium than oxygen and nitrogen. However, most helium is lost into space and its limited presence in the air today is a matter of scientific curiosity.

Both hydrogen and methane, which exist in minute quantities in the atmosphere, are products of chemical reactions on the surface of the Earth. Their stay in the atmosphere is short, because they combine with oxygen to form water and carbon dioxide.

Water is always present in the atmosphere as water vapor. Even though water vapor is present in great quantities in the atmosphere, it usually is not listed among the major components of air. Water vapor is not always and everywhere present to the same extent; over desert regions, there is very little water vapor, but over the ocean, this gas is plentiful. Moreover, the water vapor content of the air varies according to the seasons and weather conditions.

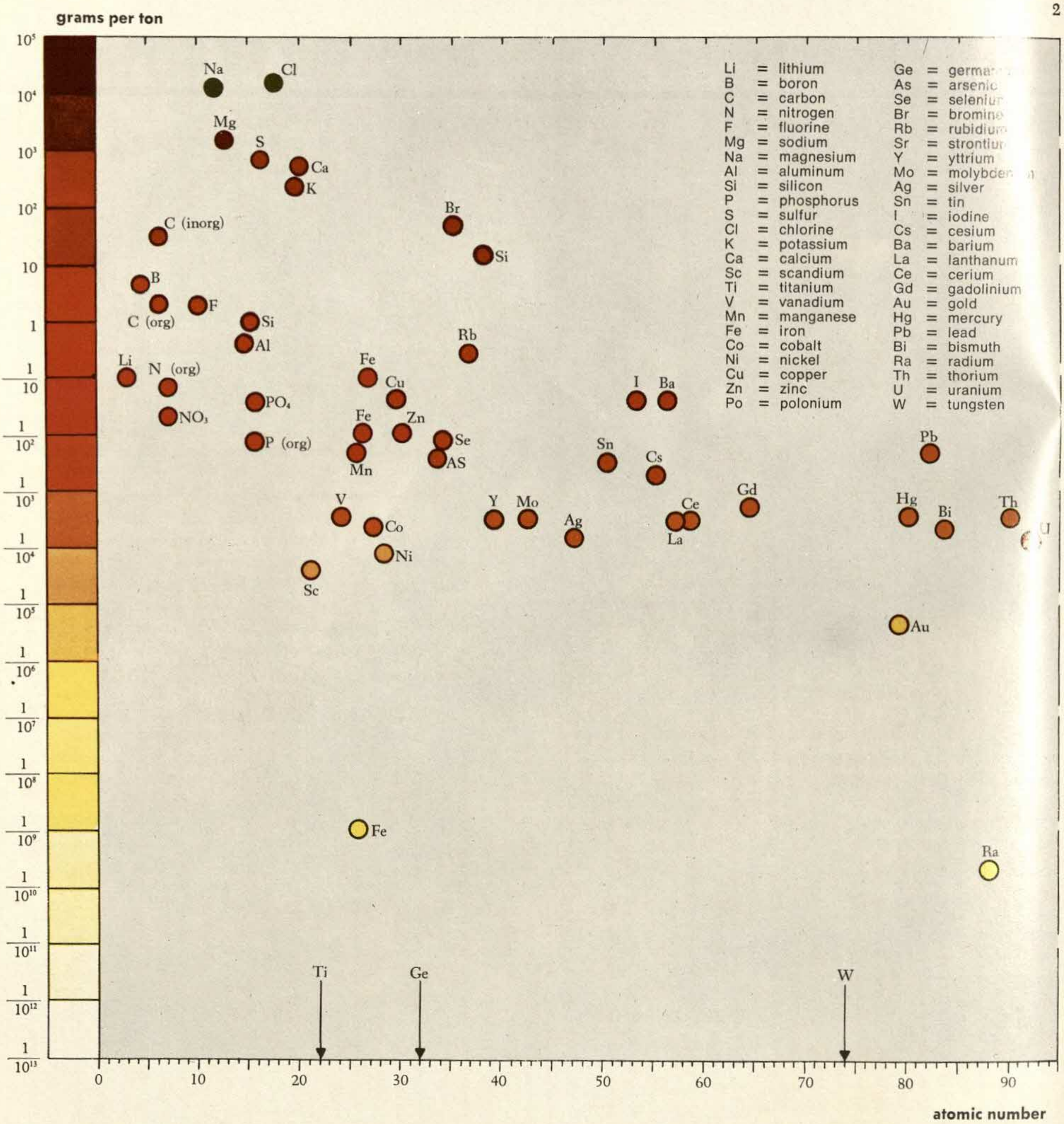
THE IMPORTANCE OF THE ATMOSPHERE

The list of components of air is more than just a dry column of numbers; it is a valuable source of information in answering questions about the history of the Earth. The atmosphere is not simply a mixture of chemicals deposited on the surface of the Earth to remain forever unchanged; rather, it is a gaseous mixture that participates actively in the chemical changes taking place on the surface of the Earth. The atmosphere, because of its composition, has largely determined the way in which life appeared and evolved on this planet; for it is the atmosphere of the Earth that supports animal and plant life. The series of rocket observations that was started in 1946 for exploring the upper atmosphere has greatly increased the understanding of Earth's atmosphere, which now can be described more precisely than ever before.

WATER SHAPES THE EARTH

how the land gets its form and the sea gets its salt

THE SEA AS A GIANT RESERVOIR—The sea, which covers two thirds of the Earth's surface, acts as a reservoir for the water of this planet. It contains particles of all the soluble elements of the Earth's crust.



THE ELEMENTS OF THE SEA—The atomic numbers of the various elements present in seawater are listed across the bottom of this graph. The relative abundance of these elements is indicated along the left-hand margin, in grams per ton of seawater. The abundance of a given element in the sea depends not only on its nuclear properties but even more on its degree of solubility in water.

Since the first rains fell and the first seas formed, water has played a major role in the dramatic events that have shaped the face of the Earth. Rivers and streams carry to the sea enormous quantities of mud and sediments, matter that was once part of mountains or other landforms. The Mississippi River annually transports to the Gulf of Mexico about 600 million tons of sediments—that is, about a fifth of a cubic kilometer of matter. If the Mississippi is the world's champion transporter of the products of erosion, other large rivers certainly are not far behind.

The Earth's surface would long since have been flattened completely if the erosive action of rivers had proceeded undisturbed for millions of years. This has not happened, of course, because other forces have been at work to counteract the leveling work of the rivers; orogenic and volcanic activities have from time to time raised certain portions of the Earth's crust, so that the erosive work of water has never been completed.

THE SEA, A MUSEUM OF ELEMENTS COMPRISING THE EARTH

When water falls on or flows over a substance, it loosens and dissolves as much of that substance as possible. If, for example, a pile of salt is located outdoors and observed for a period of time, the volume of salt will gradually be reduced. Rainwater will dissolve the salt and carry it off in solution.

Common table salt is a chemical compound (sodium chloride) that is fairly soluble in water; certain other substances, however, do not dissolve readily in water and are classified as insoluble materials; yet even these substances dissolve to some extent, however slight. For a very long time water has been dissolving the matter of the Earth's crust and carrying it to the sea. There the water is evaporated and returned (purified) to the land in the form of rain or snow. Once again the water is able to dissolve and transport to the sea part of the Earth's matter. With the repetition of this cycle, the sea becomes saltier.

It is probable that certain substances, such as table salt, were among the first to be carried down to the sea, while other substances may have required more time. The substances in the sea today are not generally found in the same proportions in the Earth's crust. Obviously, the more soluble materials are found in greater abundance in the sea than the less soluble materials. Illustration 2 shows the elements that are found dissolved in seawater.

The two most important elements are chlorine and sodium. These two are united to form sodium chloride, or table salt, which is very soluble in water. If this salt was formed originally in rocks, it was certainly washed away and carried to the sea in a relatively short time. Salt found on dry land today was not originally formed there. In Wielickza, Poland, a series of very thick underground layers of crystallized salt exists. At one time, therefore, a sea must have been located where the salt layers are situated. Because of a general rising in the land around it, this sea probably became isolated. Not being fed by a sufficient number of streams, it eventually dried up. The salt content of this sea collected and crystallized into its present form. Finally, the layers of salt were covered over and today can be found by mining underground.

When changes in drainage pattern and climate cut off lakes from their outlets to the sea, they soon become salt lakes. Great Salt Lake in Utah is an example. Standing more than 4,200 ft above sea level, it never was part of the ocean. Evaporation keeps it from overflowing; the salts leach out of the surrounding mountains and remain behind; and, in the period of about 100,000 years since its parent Lake Bonneville became isolated, the Great Salt Lake has become eight or ten times as salty as the ocean. Most of the other salt lakes, such as the Dead Sea, Caspian Sea, and Aral Sea, have acquired their salt independently of the ocean.

With the exception of deposits of this kind, sodium chloride is found for the most part dissolved in ocean water. It is interesting to note, on the other hand, that some elements that are very common on land, such as calcium and silicon, are rare in seawater, a result of the fact that they form compounds that are not readily dissolved by water. Consequently, notwithstanding the continuous action of the water, these elements have tended to remain on dry land.

Rocks on dry land contain a larger proportion of silicon compounds than calcium compounds, but this situation is reversed in ocean water because calcium salts tend to be slightly more soluble than compounds containing silicon. Finally, note in the key to Illustration 2 how little organic carbon is in the sea: only 1 to 3 g per ton of seawater. This minute quantity is that found in the bodies of marine organisms. These organisms contain other elements besides carbon, but their mass in comparison with the total quantity of seawater amounts to only about four or five parts per million.

When a living organism dies, the material comprising it is chemically changed before returning to become part of a new living organism. Therefore, when the phrase "living matter in the sea" is used, it refers to that matter that lives and lives again in the organisms inhabiting the sea. Scientists have calculated that the weight of all the matter that has been part of living aquatic organisms since the beginning of sea life is equal to the weight of the Earth. This does not imply that all the matter of the Earth has become involved at one time or another in some living organism. In their calculations, scientists have counted the weight of any atom as many times as it has returned to become part of some organism.

RARE BUT IMPORTANT ELEMENTS

Nineteen elements in seawater exist in proportions ranging from one part in a million to one part in a billion. Another 18 elements are found in proportions between one part in a billion and one part in a trillion. Three more elements are detectable under analysis, but it is difficult to ascertain their proportions.

SALT PANS—Sodium chloride is sometimes obtained by allowing seawater to evaporate completely in shallow basins or pans. The salt obtained is still impure because of the presence of other salts. Purity is obtained through a series of evaporation processes.

Finally, cadmium, chromium, thallium, antimony, zirconium, and platinum are even rarer in seawater. The most refined methods of study have not yet been able to demonstrate their presence in seawater, but they do appear in minute quantities in marine organisms. The fact that these elements appear in sea life indicates that the organisms have drawn them from seawater. Apparently these elements are so important in the lives of sea organisms that almost all of them have been drawn from the water and incorporated into certain forms of marine life.

Although most of the elements present in sea water are in quantities that a chemist would designate as traces, this term refers specifically to elements that are needed to support plant and animal life but are required in quantities much smaller than those of the carbon, oxygen, hydrogen, nitrogen, calcium, phosphorus, silicon, sulfur, sodium, potassium, and chlorine that make up 99.9 percent of the weight of living organisms. They are not needed for general tissue building or skeletal formation, but they enter into specific compounds that serve, for example, as catalysts in respiration. Some of these elements are magnesium in the chlorophyll molecule, iron in hemoglobin, copper in the hemocyanin of crustaceans, iodine in thyroxin, and fluorine in teeth. Trace elements in general are abundant enough in the ocean to serve the needs of most marine organisms. Exceptions are the vanadium-rich holothurians and tunicates. Their blood contains up to 10 percent vanadium, which is 50 million times as much as there is in seawater. The role of vanadium in their metabolism is not yet fully understood.

MARINE MORTALITY

Along with the factors that encourage marine life are physical and chemical relationships in the ocean that destroy life. Vertical mixing, for example, can carry to the surface water that is low in oxygen (as in Walvis Bay, South-West Africa) or high in hydrogen sulfide (as in the Black Sea) with fatal results to the surface fauna. Another destructive phenomenon is uncommonly heavy growth of dinoflagellates in the surface layers. These one-celled aquatic organisms produce toxic substances that result in vast kills of marine life. In many parts of the world, they multiply in such numbers from time to time as to color the ocean red—thus, the dreaded "red tides."

THE INTERIOR OF THE EARTH

the story told by seismic waves

Men make temporary excursions into the atmosphere, and they even venture into outer space for limited periods of time. But they have not explored the interior of their own planet to any great extent.

Mine shafts have been sunk into the Earth's crust to a depth of about 3,000 m (about 10,000 ft), and men have descended beneath the surface of the ocean in bathyscaphes to a depth of just over 10,000 m (over 33,000 ft). Soundings of the Earth's crust have been made to a depth of less than 10 km (about 6 mi). Still, these penetrations of the Earth's interior seem insignificant in light of the fact that the Earth's center lies about 6,380 km (about 4,000 mi) below the surface.

The interior of the Earth, for the most part, is inaccessible to direct observation. What, then, men have been able to learn about the nature of the planet's interior they have had to learn indirectly through various methods.

THE STUDY OF EARTHQUAKES

A child—or an occasional adult—may try to guess the contents of a package that should not be opened prematurely, such as a birthday or Christmas present. He may weigh the package in his hand. He may shake it in an attempt to determine from the noise and the movement whether the package contains a single article or several articles or a liquid. He may also try to determine whether the contents are held together tightly or are free to rattle around.

Scientists can use a remotely similar method to determine the structure of the Earth's interior. Obviously, they cannot hold the planet in their hands and shake it, but they can make use of the forces that cause the Earth to shake and tremble. They can study the vibrations or seismic waves generated by earthquakes and artificially produced explosions.

The Earth is continually subjected to tremors, which on the whole are not very important. However, earthquakes do occur frequently and sometimes disastrously in certain parts of the planet. Scientists have established earthquake study centers in many of these areas for the purposes of locating the origins of seismic waves, studying their movements, advising means of minimizing the effects of earthquakes on buildings, and, if possible, predicting when earthquakes will occur.

Seismologists, the scientists who study seismic phenomena, try to locate the hypocenters, or foci, of earthquakes (the points of earthquake origins inside the Earth) and the epicenters (the points on the Earth's surface directly above the hypocenters). In addition, they study the velocities and paths of seismic waves deep inside the Earth.

Three basic types of seismic waves are known. The fastest of them are the so-called body waves: the primary or P-waves and the secondary (shear) or

COMPRESSIONAL WAVES — This idealized block (Illustration 1) shows how the ground is compressed (the dark sections) as compressional waves (P-waves) pass. These waves cause the alternate compression and expansion of the ground. The black line represents the motion of a single particle of matter when the compression wave passes. This motion obviously is very slight in comparison with the total wavelength of the earthquake. Any kind of ground can transmit longitudinal or compressional waves.

TRANSVERSE WAVES—Illustration 2 shows how the energy of a transverse wave (S-wave) is transmitted in one direction, while the particles of the transmitting matter are moved in a direction perpendicular to the direction of wave and energy transmission. Transverse waves are transmitted only by solid matter; they cannot travel in a fluid. The outer core of the Earth is probably fluid, starting at the point at which transverse waves are no longer transmitted. Seismologists infer that liquid lies below a 2,900 km (1,800 mi) depth.

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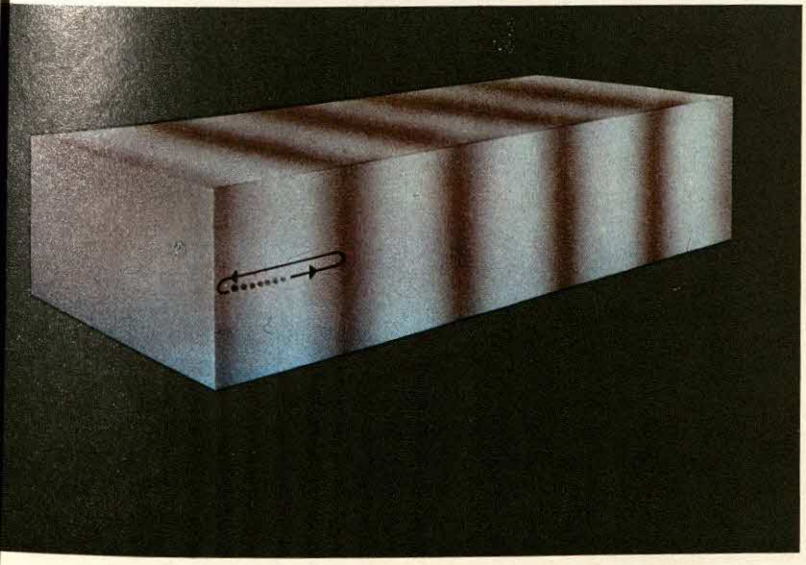

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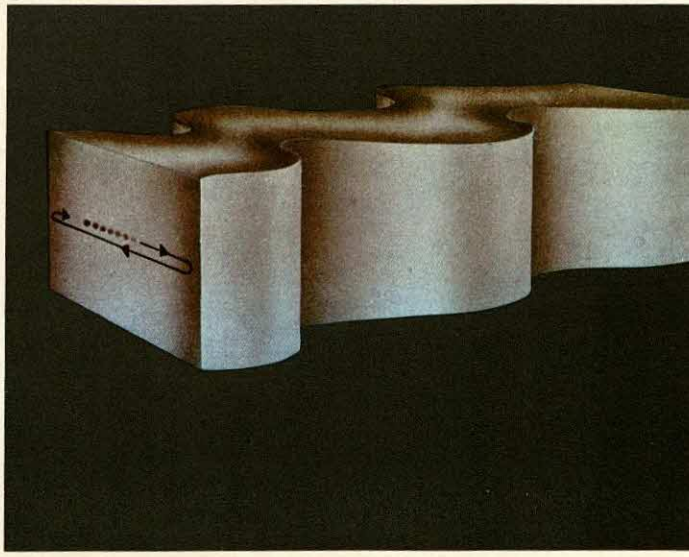

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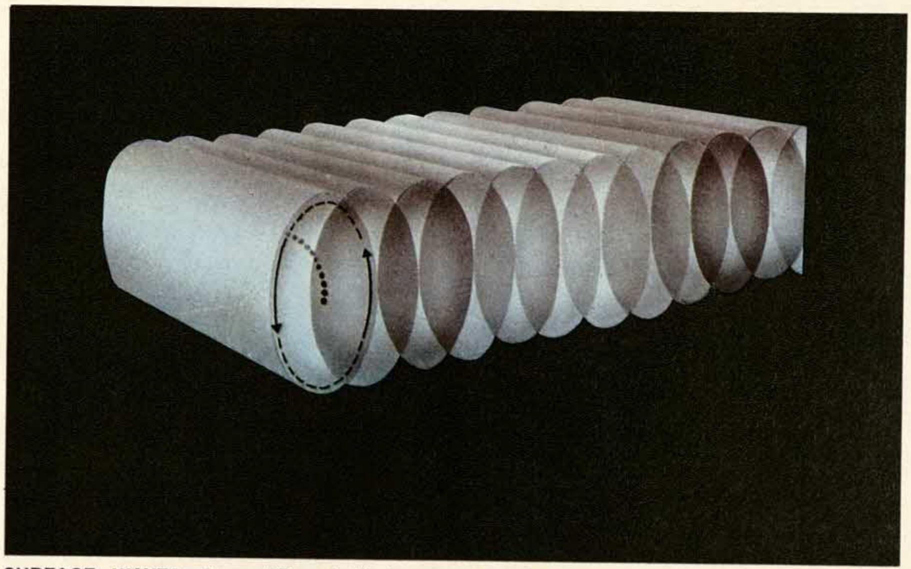

SURFACE WAVES—Four different kinds of surface waves have been studied, the most common of which are known as L-waves. The movement of these waves is similar to the motion of waves produced in a pond when a stone is thrown into the water. Each particle of matter follows an elliptical pattern, as shown in Illustration 3.

S-waves. Following an earthquake, the P- and S-waves spread out from the hypocenter in all directions, passing right through the Earth. The surface waves, often designated L-waves, are restricted, in their movement, to the surface of the Earth.

Primary waves are also known as compressional waves, for they travel in a manner similar to acoustical or sound waves—that is, by the compression and rarefaction (thinning out) of matter. P-waves involve a back-and-forth motion in which particles are compressed or pushed together and then rarefied or pulled apart. By way of analogy, a coiled spring, which may be alternately squeezed together and stretched, may be considered.

Following an earthquake, P-waves travel through the Earth, alternately compressing and thinning out the matter through which they pass, even at a considerable distance from the original point of disturbance. Earth disturbances of this kind can happen because the Earth behaves as a solid but elastic body. It loses volume when it is squeezed or compressed, but expands and regains volume when this action is completed. All solid materials, including rocks, have this property. However, the volume of a solid cannot be reduced very much by compression. On the other hand, gases, such as those comprising the atmosphere, can be compressed enormously.

Compressional waves are also called longitudinal waves, because the particles that participate in the propagation of the waves move in the same direction as the waves themselves.

Secondary or S-waves are also called transverse waves, because they involve the oscillation of particles in a direction that is perpendicular to the line along which the wave travels. No equivalent is found in acoustics, for transverse waves do not travel in air, water, or any other fluid medium.

To gain a better understanding of S-waves, tie a length of cord or rope to a doorknob. Hold the free end of the rope so that no part of the rope touches the floor. Then give the rope a sudden shake or jerk. An S-wave may be observed to travel the entire length of the rope. Small segments of the rope are moved to one side—in the direction in which the rope was jerked. The energy of that action, however, travels along the rope in a direction perpendicular to that of the original movement.

P-waves and S-waves, which have their origins deep inside the Earth, produce surface waves similar to those produced on the surface of a pond when a pebble or stone is thrown into the water. Four different kinds of surface waves have been identified, the most common of which are called L-waves. The less common varieties are combinations of oscillations that are simpler than those just described.

THE PROPAGATION OF SEISMIC WAVES

Basically, all three varieties of waves are produced when an earthquake occurs. It has already been noted that P-waves are produced by a back-and-forth, longitudinal motion of a block of Earth while S-waves involve a lateral or transverse motion. However, S-waves are emitted from the sides of a block of Earth that is moved longitudinally, and P-waves are produced from the ends of the block that is moved laterally. On the surface of the Earth, both P- and S-waves produce L-waves. The study of a given earthquake must take into account all three kinds of waves, each traveling at a different speed. Calculations must include not only the kind of wave involved, but also the material through which it passes and the amount of pressure to which this matter is subjected. The greater the distance from the Earth's surface, the greater the pressure and the velocity of the wave.

Surface waves or L-waves vary in velocity, depending on both the geological characteristics of the surface and the nature of the wave itself. The characteristics of L-waves can be conditioned by the manner in which they are produced and by the character of the ground through which they must travel. Both these factors occasion a large variation in both the speed and form of L-waves. Generally, however, L-waves move more slowly than P-waves and S-waves.

L-waves have wavelengths ranging between 40 and 70 km (about 25 to 45 mi), but some with even longer wavelengths have been detected. L-waves with wavelengths of about 80 km (about 50 mi) will raise and lower a given point on the Earth's surface about once every 20 seconds.

P- and S-waves, which are faster than L-waves, travel both deep inside the Earth and on the surface; therefore, a knowledge of their subterranean velocities is important to an understanding of their motions. The following table gives the velocity of P- and S-waves:

Depth, km	Speed of P-waves km/sec	Speed of S-waves, km/sec
50	8.2	4.45
100	8.0	4.4
150	7.9	4.35
200	8.0	4.4
250	8.2	4.5
300	8.3	4.6
500	9.6	5.3
1,000	11.6	6.4
1,500	12.2	6.7
2,000	12.8	6.9
down to 2,900	13.7	7.3
below 2,900	8.0	
4,000	9.4	
5,000	10.0	
5,400	11.1	
6,370	11.2	

Study of this table reveals some interesting relationships. First of all, P-waves, at any depth, travel about twice as fast as S-waves. Secondly, pressure increases are accompanied by increases in the velocity of each variety of wave. However, exceptions do exist. P-waves have a certain velocity from the surface down to a depth of 50 km (about 30 mi), at which point the velocity decreases sharply. At a depth of 100 km (about 60 mi), the speed is only 8 km/sec (about 18,000 mph). The speed then increases regularly down to a depth of 2,900 km (about 1,800 mi), where it reaches 13.7 km/sec (about 30,500 mph). Slightly farther down, P-waves move even more slowly; at a depth of a little over 2,900 km (about 1,800 mi), they travel at a speed of only 8 km/sec. Once again, the speed increases continually with further increases in depth.

In sum, sudden changes in the speeds of seismic waves are noted at different levels or depths inside the Earth. Probably these changes are due to variations in either the composition or the state of matter at any given level.

Examination of the S-wave column in the table suggests that further investigations of the Earth's interior are needed. It seems that S-waves do not travel below a depth of 2,900 km. It is probably more than coincidental that at this same depth the P-waves exhibit a sharp change in velocity. It has already been noted that S-waves do not travel in liquids or gases. From this evidence, scientists have concluded that the nucleus of the Earth is fluid.

THE INTERNAL STRUCTURE OF THE EARTH

The composition of the interior of the Earth has long been a subject for fanciful speculation. Present-day scientists have the knowledge and the tools to sort out fact from fancy. As indicated previously, one way of learning about the Earth's interior is to study the vibrations or seismic waves generated by earthquakes and artificially produced explosions. Interpretation of the movements of seismic waves would be simple if the Earth were homogeneous; these waves would spread in a straight line from the source of the earthquake as far as they could reach. But the Earth is not homogeneous, and the movements of seismic waves are very complicated. For each variation in speed or direction, scientists

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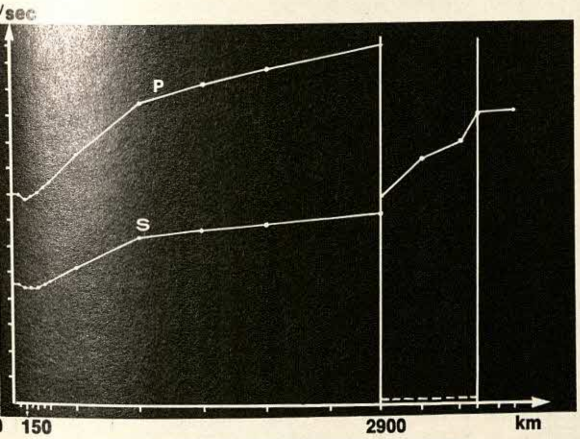

THE SPEED OF SEISMIC WAVES—Generally, the speed of seismic waves increases with depth. Below a depth of 2,900 km (about 1,800 mi), transverse waves disappear. At this point, the speed of longitudinal or compressional waves decreases sharply and then increases (Illustration 4).

WAVES PASSING THROUGH THE EARTH—Illustration 5 shows how seismic waves (in this case P-waves) travel through the Earth. The motion of solid particles in the Earth causes objects on the surface to shake; this motion may cause buildings to collapse. The length of a wave (that is, the distance between two successive compressions) is frequently several kilometers. However, because the waves travel at a high velocity, the shaking is frequent.

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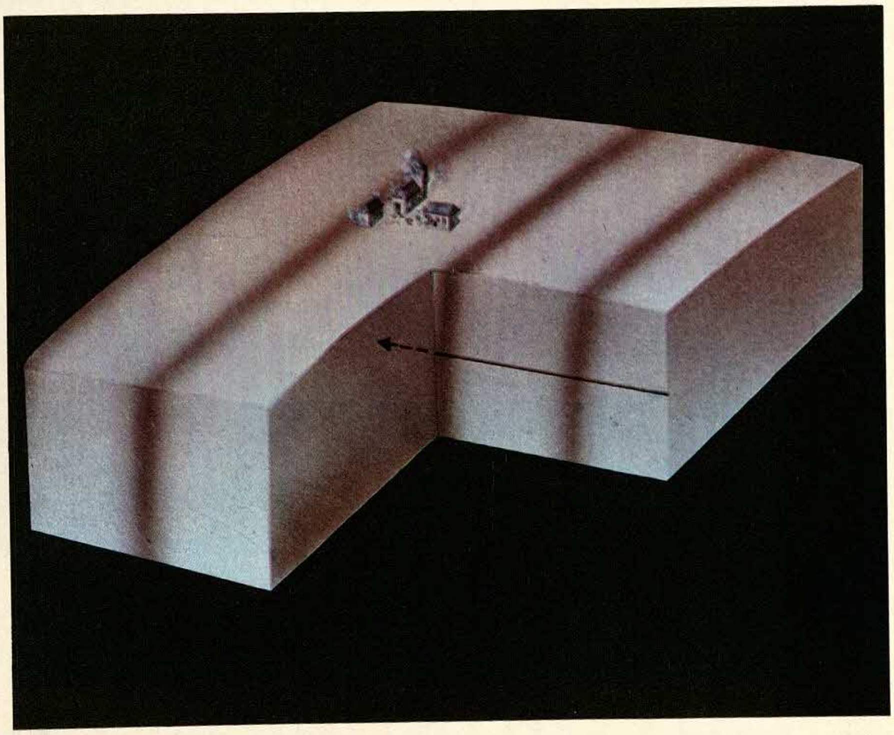

infer that a discontinuity or variation exists in the composition of the materials through which the waves have passed.

At a depth varying between 10 and 50 km (about 6 to 31 mi), the first discontinuity or boundary between different kinds of rock is found. This discontinuity is named for Andrija Mohorovicic, a Croatian geologist, and it is usually referred to as the Moho or M discontinuity.

Studies of the reflections of seismic waves have located the Moho at modest depths beneath the ocean floor and at average depths of 30 to 40 km (about 19 to 25 mi) beneath the continents. Its greatest depth is beneath the large mountain masses. Extensive data on the depth of the Moho have been compiled in recent decades.

The metamorphic, granitic, and basaltic rocks lying above the Moho form the Earth's crust. These are the rocks that have undergone erosion during the various geological eras. The products of erosion were deposited on these older rocks and cemented together to form new rocks: the sedimentary rocks. The crust varies greatly in thickness, being very thin beneath the oceans and considerably thicker beneath the continental masses, but it is present over the entire surface of the Earth.

Three minor discontinuities are located beneath the Moho at depths of about 70 to 200 km (about 45 to 125 mi), 400 km (about 250 mi), and 900 km (about 560 mi). The region from 70 to 200 km represents a low velocity zone that may be a region of partial melting. The most important discontinuity, however, lies about 2,900 km (about 1,800 mi) beneath the surface of the Earth. Here (as indicated previously) the speed of seismic waves decreases sharply; moreover, the zones beneath this depth do not transmit S-waves. Seismologists infer that the material below a depth of 2,900 km is in a liquid state, because liquids do not transmit S-waves.

The layer between the lower edge of the Earth's crust and the discontinuity at 2,900 km is called the mantle. The liquid matter found below a depth of 2,900 km is called the core. It may represent a change from the solid silicate of the mantle to a fluid iron-nickel compound. The core is divided into an inner and an outer part by a discontinuity at a depth of about 5,100 km (about 3,1[illegible] mi). The inner core may consist of the same kind of material as the fluid outer core, but it is in a solid state because of high pressures. Some hypotheses concerning the temperature and density of matter near the center of the Earth help provide an understanding of this situation.

THE PATHS OF SEISMIC WAVES—Seismic waves of the P and S types travel through the Earth along the same curve, but at different speeds. That part of the Earth's crust with a vertex diametrically opposite an earthquake's epicenter receives no S-waves—as though there were a shield at the center of the Earth that can be penetrated only by P-waves.

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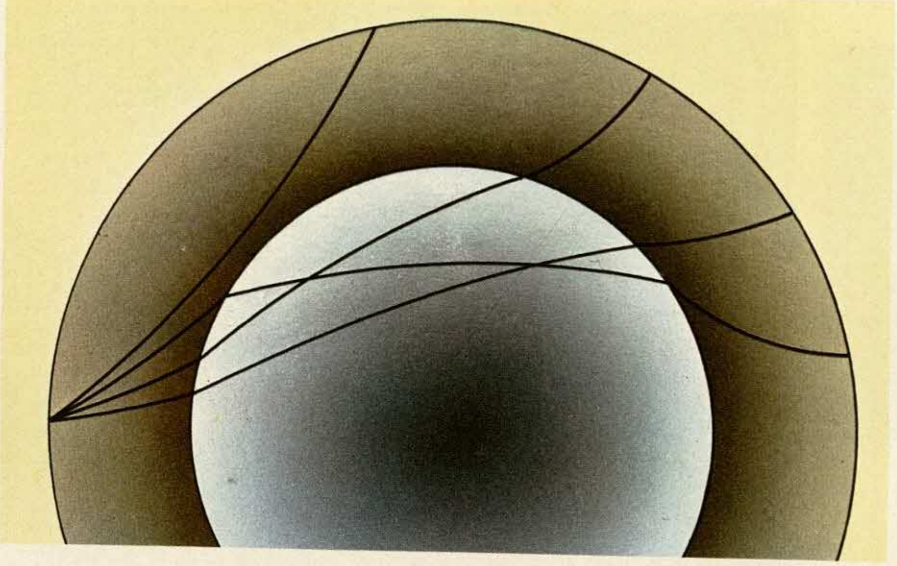

DENSITY, TEMPERATURE, AND COMPOSITION OF THE DEEP STRATA

Men boring holes in the ground for mines, tunnels, and wells have discovered that the temperature increases about 30 C° (about 54 F°) for every kilometer increase in depth—with the exception of the first few yards below the surface, where the temperature depends on meteorological conditions. In the past, this observation led to the belief that the temperature would continue to increase all the way to the center of the Earth, where it would be more than 100,000° C (about 180,000° F), but this hypothesis has now been discredited.

The heat that rises continually to the surface of the Earth is actually produced in the rocks of the crust and upper mantle by the radioactive elements contained in them. Below the Moho—that is, in the mantle—the temperature rises more slowly than it does in the crust, perhaps 5 to 10 C° beneath the continents and 10 to 15 C° beneath the oceans. At the bottom of the crust, the temperature varies between 400 and 800° C (about 750 and 1,500° F). Scientists estimate, on the basis of laboratory measurements, that temperatures should not exceed 1,500° C (about 2,700° F) at a depth of 200 km (about 125 mi); at a depth of 2,900 km (about 1,800 mi), where the top of the core is located, temperatures have been estimated to be about 3,000° C (about 5,400° F).

Modern geophysical knowledge makes it possible to estimate the temperatures at these inaccessible depths. The Earth's crust is solid and rigid. Scientists have bored into the crust and made measurements of the temperature increases under the surface. These indicate that the rocks must still be solid at the inner edge of the crust, because their exact composition (similar to ordinary granite) and their melting point are known. Thus, the temperature at the average depth of the Moho is calculated at between 400 and 800° C (about 750 and 1,500° F).

Both the crust and the mantle transmit P-waves and S-waves. Therefore, they behave as solid and rigid bodies. The rocks comprising them are subjected to high pressures; generally speaking, the greater the pressure, the higher the melting point of solids. Scientists have not yet been able to make measurements of melting points at the high pressures expected within the lower mantle, but they have suggested that mantle materials may exceed temperatures of 2,000 to 2,500° C (about 3,600 to 4,500° F) without melting.

Seismology helps to explain what occurs at depths between 400 and 900 km (about 250 and 560 mi). Earthquakes do not occur with hypocenters lying deeper than about 700 km (about 430 mi). The most frequent causes of intermediate and deep earthquakes are tensional and compressional forces within the mantle; near-surface earthquakes may have other causes. The slow movement of huge rock masses—almost the size of continents—can compress and fracture rocks. Many years are needed for forces to exceed the strength of a rock, but ultimately the rock may break and cause an earthquake. If the rock is "pasty," its shape changes as it is subjected to pressure.

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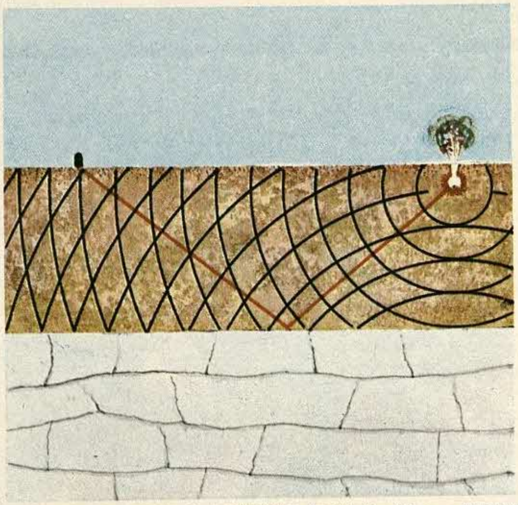

THE REFLECTION OF SEISMIC WAVES—The seismic waves of an earthquake produced by an explosive charge are reflected back to the surface after making contact with a layer of different composition. The depth of one layer of discontinuity can be calculated from the position at which the reflected wave is received and the time it takes to arrive. This method of studying seismic waves is called reflection prospecting.

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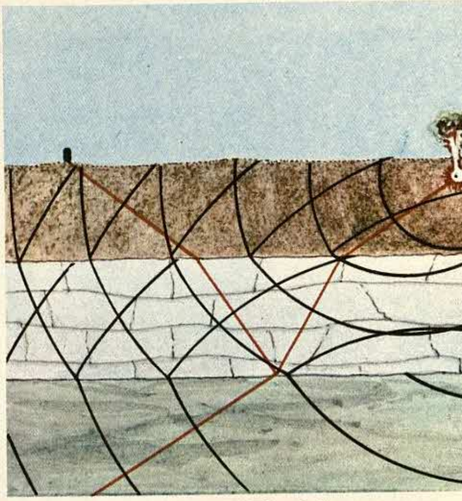


THE REFRACTION OF SEISMIC WAVES—Seismic waves are refracted (that is, they change direction and speed) as they pass through layers of the Earth having different compositions. From the time taken by the waves to reach listening posts, scientists can deduce the thicknesses of the layers through which they have passed and, within certain limits, their composition. This technique is called refraction prospecting.

The outer core of the Earth is probably liquid because it cannot transmit S-waves. However, geophysicists suggest that the central part of the core may be solid. They have observed that P-waves passing diametrically through the Earth arrive late—as though they were changed into the slower-moving S-waves at a depth of about 5,100 km (about 3,150 mi) and then back into P-waves after passing through this hypothetical solid "kernel."

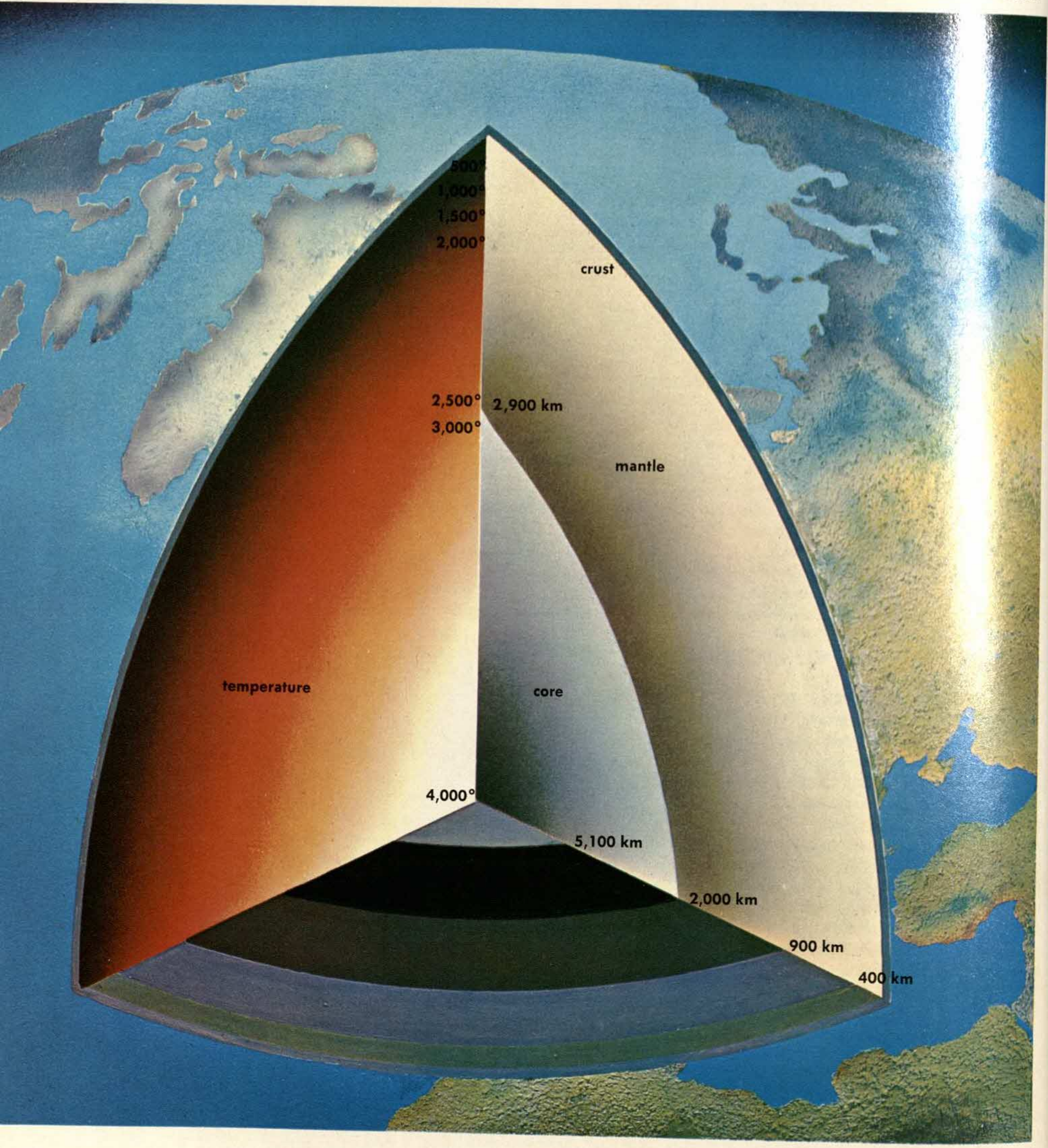
If temperatures in the core were not higher than 4,000° C (about 7,200° F), the pressures beneath a depth of 5,100 km could keep the central part of the core in a solid state. Because the propagation of seismic waves shows that the rocks there must be solid, it is quite likely that the temperature at the center of the Earth does not exceed that of about 4,000° C.

The view that the Earth's outer core is most likely composed of molten iron has been generally accepted for many years. A small amount of nickel and some other impurities might be dissolved in the fluid mass. The view that the core consists of iron fits all the known physical and chemical facts, and it agrees with the seismic data. The melting point of iron at high pressures is much lower than that of the compact silicates, explaining the sharp discontinuity at the boundary of the core.

The composition of the inner core is in doubt; but it is known that the sum total of all the elements heavier than iron—relative to the main constituents of the Earth—is not remotely enough to fill a volume the size of the inner core. Thus, it usually is assumed that the inner core consists of iron solidified under extreme pressures.

INSIDE THE EARTH—The Earth is made up of various strata of matter (to the right and below). The temperature varies from 400 to 800° C (about 750 to 1,500° F) at the base of the crust to about 4,000° C (about 7,200° F) in the core (at left).

▨	**solid core**	⬛	**plastic rocks**	🟩	**olid rocks**
⬛	**fluid core**	🟦	**transition zone**	🟦	**lid crust**



THE EARTH'S MASS AND DENSITY

universal gravitation provides the answer

More detailed knowledge of the Earth's structure has resulted, in large measure, from the vastly improved instruments and methods used in the study of earthquakes—the science of seismology. The techniques used in this science are certainly the most important methods used to probe the internal regions of the Earth; however, other techniques exist, including the measurement of slight variations in gravitational attraction between two points on the Earth's surface.

The density of the deep layers of the Earth can only be known by determining first, the mean density of the Earth and second, the density of its accessible regions near the surface. The mean density of the Earth is known to be 5.52 times that of water (which is taken as unity). Density is calculated by determining separately the mass and volume of an object, and is in fact the ratio between these two magnitudes (mass/volume—more precisely, mass in grams/volume in cubic centimeters, or g/cm^3). Among the various methods used for calculating the Earth's mass are astronomical measurements and precise laboratory scales, such as the Jolly balance named for the nineteenth-century German physicist, Philipp von Jolly.

UNIVERSAL GRAVITATION

Every particle of matter in the universe attracts every other particle by a force, called gravitation, that depends on the mass of the particles involved and their distance from each other. A large mass exercises greater gravitational force than a small mass; and the less the distance between the objects, the greater the gravitational force. Some gravitational force always exists, however, no matter how great the distance: a man's body exerts gravitational attraction on the lamp in the window of a house across the street; that house exerts force on a bus moving down a street in a nearby city; the bus exerts force on a far-off galaxy. In the same way, and very directly, the Earth attracts the moon, and the sun attracts the planets. These are all examples of the law of universal gravitation, which states that two masses of matter attract each other with a force directly proportional to the product of their masses and inversely proportional to the square of the distance between them. If the masses are homogeneous, spherical bodies, the distance is understood as the distance between their centers; this applies particularly to celestial bodies. The law can be expressed mathematically:

$$F = \frac{m_1 \times m_2}{r_2} \times G.$$

In the special case where a small mass at the Earth's surface is being considered, m_1 is the Earth's mass (5.983×10^{27} g), m_2 is 1,000 g (10^3 g), and r is the distance between the centers of the masses m_1 and m_2 and is almost equal to the equatorial radius of the Earth, 6.378×10^8 cm.

G is the constant of universal gravitation, which is used to find the value of the force in appropriate units of measurement (in this case, the CGS, or centimeter-gram-second, system): 6.670×10^{-8} cm^3/g sec^2. Therefore, the force acting on a mass of 1 kg is

$$F = \frac{10^3 \times 5.983 \times 10^{27}}{(6.378 \times 10^8)^2} \times 6.670 \times 10^{-8} = 980{,}000 \text{ dynes.}$$

(The dyne is the unit of force in the CGS system.)

If the value of G is known, it is fairly simple to calculate the Earth's mass. Assume that the force exerted by the Earth on a mass of 1 kg is known: 980,000 dynes. If the constant G is known, and the distance between the center of the Earth and the location where the measurement of the attraction is to take place is known, the only unknown magnitude is the mass of the Earth, which can be calculated by using the first formula above, resolved thus:

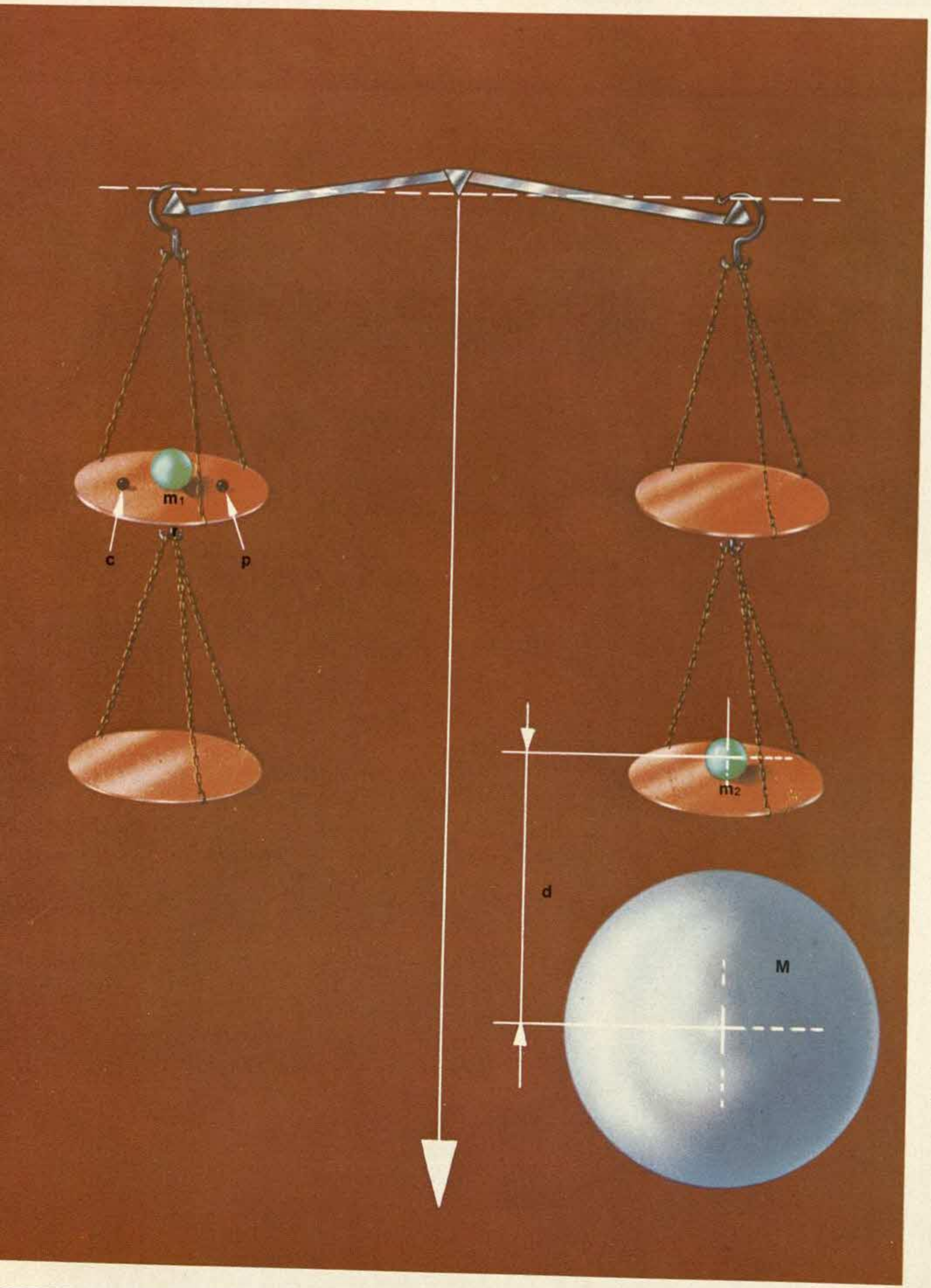
$$m_1 = \frac{F \times r^2}{G \times m_2}.$$

The value of G is calculated by means of a torsion balance, and must be studied separately.

THE MASS AND THE DENSITY

The most precise estimate of the Earth's mass is 5.983×10^{27} g. Inasmuch as the Earth's volume has been calculated to be 1.083×10^{27} cm^3, its density is easily determined by dividing its mass by its volume: $5.983 \times 10^{27}/1.083 \times 10^{27} = 5.522$ g/cm^3 (grams per cubic centimeter). This is the Earth's mean density. The Earth is composed, of course, of materials with densities that differ from this mean. In the outer layer, the crust, which is partially accessible, the density of the known rocks is about 2.7 g/cm^3. The predominant elements in the rocks of the crust are silicon and aluminum, and from the first syllables of these two words scientists have coined the word "sial" to designate rocks of this general composition and density.

At the border between the crust and the mantle—the so-called Moho, named after the Croatian geophysicist A. Mohorovicic—the seismic waves are found to undergo a sharp increase in velocity, and the exact magnitude of this acceleration makes it possible to identify the general composition and density of the rocks that compose the mantle, the layer below the crust. The rocks of the mantle are believed to be similar to the basalts and peridotites—basic rocks, without quartz—found sometimes on the Earth's surface, with a density of about 3 g/cm^3. The density of the mantle, just below the crust, is estimated at about 3.3 g/cm^3. The mantle rock is predominantly composed of the elements silicon and magnesium (with considerable iron), and so the word "sima" was coined to designate such rocks. The density of sima increases with depth, and this is to be expected; for if all the rocks were of a



WEIGHING THE EARTH IN A LABORATORY—In order to carry out this experiment, it is necessary to have a precision balance with four identical pans; two identical balls m_1 and m_2; and a large lead sphere M. If m_1 and m_2 are placed on the upper pans, they will balance each other. If m_2 is moved to the lower pan on the side of the scale—that is, closer to the center of the Earth—the equilibrium will no longer exist; it can be restored by adding a small weight p to the pan holding m_1.

Now, if the large sphere M is placed close to m_2, it will exert a perceptible amount of attraction on that ball and a negligible amount on m_1, which is some distance away. Once more the equilibrium is lost; this time it is restored by adding another small weight c to the pan holding m_1. This proves that mass M attracts m_2 with the same amount of force as the Earth attracts c.

The formula for the law of gravitation can be applied to this situation by substituting first M and then E (the unknown mass of the Earth) for m_1 in the original equation; by substituting m_2 and then c for m_2 in that equation; and by substituting d (the distance between M and m_2 in this experiment) and then r (the Earth's radius) for r in that equation:

$$F = \frac{m_1 \times m_2}{r^2} \times G$$

(original equation);

$$\frac{M \times m_2}{d^2} \times G; \frac{E \times c}{r^2} \times G.$$

Inasmuch as these last two expressions are equal, if E is taken as the unknown magnitude the equation can be resolved thus:

$$E = \frac{M \times m_2 \times r^2}{c \times d^2},$$

and from this equation a value of 6.15×10^{27} g will be obtained.

density of 3.3 g/cm³ or less, it would be impossible to account for the mean density of the Earth of about 5.5 g/cm³. Somewhere rocks that have a density greater than 5.5 g/cm³ must exist.

At a depth of 400 km (about 250 mi), the density of the mantle is estimated at about 4 g/cm³; at 900 km (about 560 mi) at about 4.4 g/cm³; at 2,900 km (about 1,800 mi) at about 5.6 g/cm³. Below 2,900 km matter is extremely dense, and this depth may be considered the end of the mantle and the beginning of the core. The density is believed to range from about 9.7 g/cm³ where the outer core begins, to about 12 g/cm³ at a depth of 5,100 km (about 3,200 mi) below the surface, and toward the Earth's center to about 15 g/cm³.

Although the pressures at these depths must be very great, they do not account for such high densities; it is not likely that simatic rocks are compressed to make them as dense as this. It is more probable that the core is composed of elements already very dense even under ordinary pressures. The most plausible hypothesis is that these are the same very dense elements that compose stars and that are found in meteorites. The latter are assumed to be small bodies of stellar matter or planetary fragments condensed from stellar matter, all of which have lost some of the lighter elements found on Earth. The meteorites are easily analyzed, and although their composition varies, the main elements are iron and nickel. Under ordinary pressure, iron has a density of 7.86 g/cm³ and nickel a density of 8.9 g/cm³. Under the pressures in the center of the Earth, these densities could rise to 10 or 15 g/cm³.

Although scientists have long conjectured about the state of matter in the core of the Earth, it has been possible to find some answers recently by reproducing in the laboratory conditions fairly similar to those thought to exist within the Earth's interior. This has been accomplished by creating extremely high pressures, of hundreds of thousands of atmospheres, at temperatures of up to 2,000° C (3,632° F).

Traditional dogmatic geochemical speculation has dealt with the formation of the Earth largely in accordance with the processes that take place in ore-smelting furnaces—as though the Earth was once totally molten. By the 1970s, however, considerable evidence indicated that the Earth and other planets were formed at low temperature by condensation and accumulation from a dust cloud. Harold C. Urey, U.S. chemist and Nobel laureate, developed the new approach in detail, mainly on the basis of thermodynamic considerations. According to Urey, the final accumulation of the Earth took place at a temperature of about 0° C from small planetesimals (solid heavenly bodies that may have existed at an early stage in the development of the solar system) containing metallic iron, carbon, iron carbide, titanium nitride, and some ferrous sulfide. A gas phase had mainly been lost during an earlier high-temperature stage, and only small amounts of hydrogen, nitrogen, inert gases, water vapor, methane, and hydrogen sulfide were left. The iron core of the Earth accumulated slowly during the geological history of the Earth from an almost uniform mixture of metallic iron and silicates, according to Urey's theory. Geological time started when a stable crust formed and exogenic processes began.

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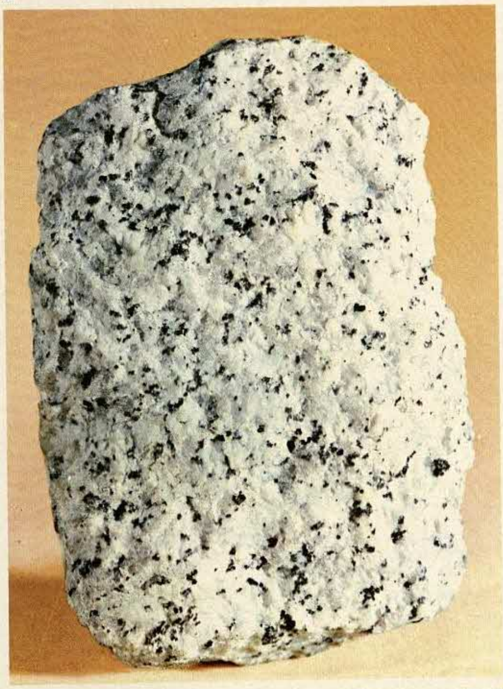


GRANITE—This acid igneous rock (Illustration 2), rich in silicon, has a density that makes it representative of the Earth's crust. Granite is by far the most common rock known or suspected to be of magmatic origin.

3

DUNITE—This basic rock (Illustration 3) found on the Earth's crust is similar to peridotite and has a composition that is believed to be similar to the rocks of the mantle of the Earth at depths of more than 60 km (about 37 mi).

THE EARTH'S CRUST

the composition of the lithosphere

←**STUDIES FROM SPACE**—Photographs taken from space are of great help in geological studies of the distribution of land and sea. This photograph was taken from a U. S. Atlas mission at an altitude of about 1,200 km (about 750 mi).

Throughout the ages, man has thought of the land beneath his feet as "terra firma"—solid ground. Modern geological science has demonstrated that the planet Earth is not as solid as it may seem. While there is still much to be learned—particularly about the internal composition of the Earth—the elements that make up its outer crust have been identified and cataloged.

THE LITHOSPHERE, OR OUTSIDE OF THE EARTH'S CRUST

The composition of the lithosphere has been determined through analyses of the most common types of rocks and subsequent estimates of their abundance.

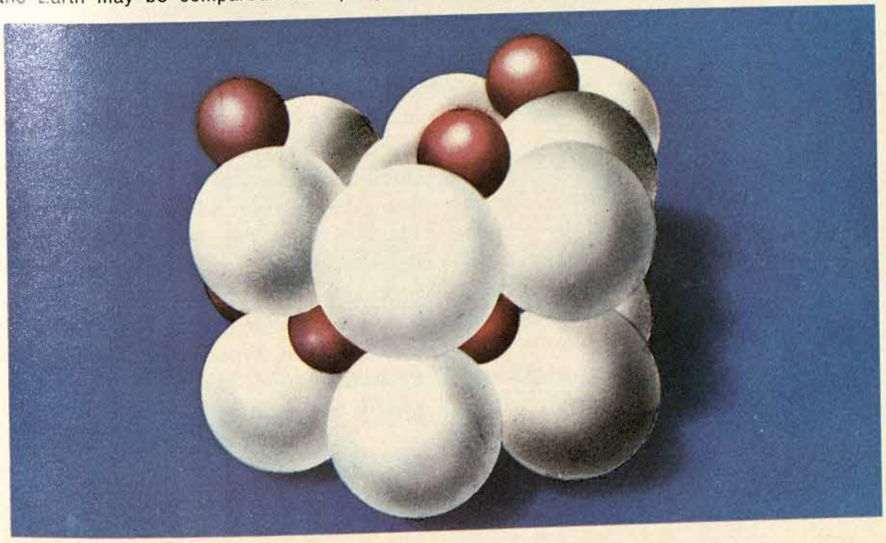
Element	*Percentage by weight* (Clarke and Washington)
oxygen	46.60
silicon	27.72
aluminum	8.13
iron	5.00
calcium	3.63
sodium	2.83
potassium	2.59
magnesium	2.09

Many scientists have worked independently on these calculations; their results have been in perfect agreement. The table gives the percentage by weight of the most common elements in the lithosphere.

The most abundant element is oxygen, which alone accounts for almost half the weight of all the elements present. Next is silicon, which makes up less than a third of the total weight. Aluminum and iron are also very abundant, even though the abundance of the latter in the lithosphere is very small in comparison to the amount believed to exist in the core of the Earth.

The lithosphere also contains other known elements in lesser proportions. Their presence is indicated in Illustration 5, where the elements are shown in order of their decreasing abundance. The only elements lacking in the rocks of the lithosphere are technetium, promethium, astatine, radon, francium, and the transuranic elements with an atomic number higher than 92. Because of its structure, the nucleus of technetium is not likely to be found inside stars, so there is little likelihood of finding the element in a planet like the Earth. To date, it has only been produced artificially (the Greek word *technetos,* from which this element takes its name, means "artificial"). Promethium is also rare, or totally absent, for the same reasons. Astatine, radon, and francium are radioactive and therefore decay quickly, turning into other elements.

A SPONGE OF OXYGEN—The outer crust of the Earth may be compared to a sponge of large oxygen atoms. Oxygen accounts for almost 92 percent of the lithosphere's space.

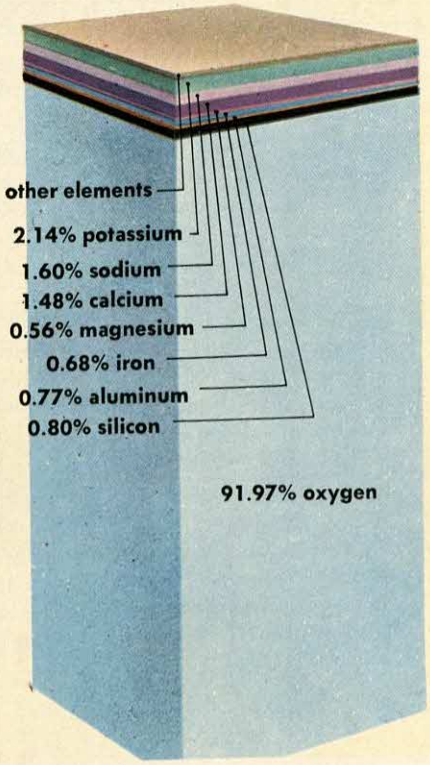


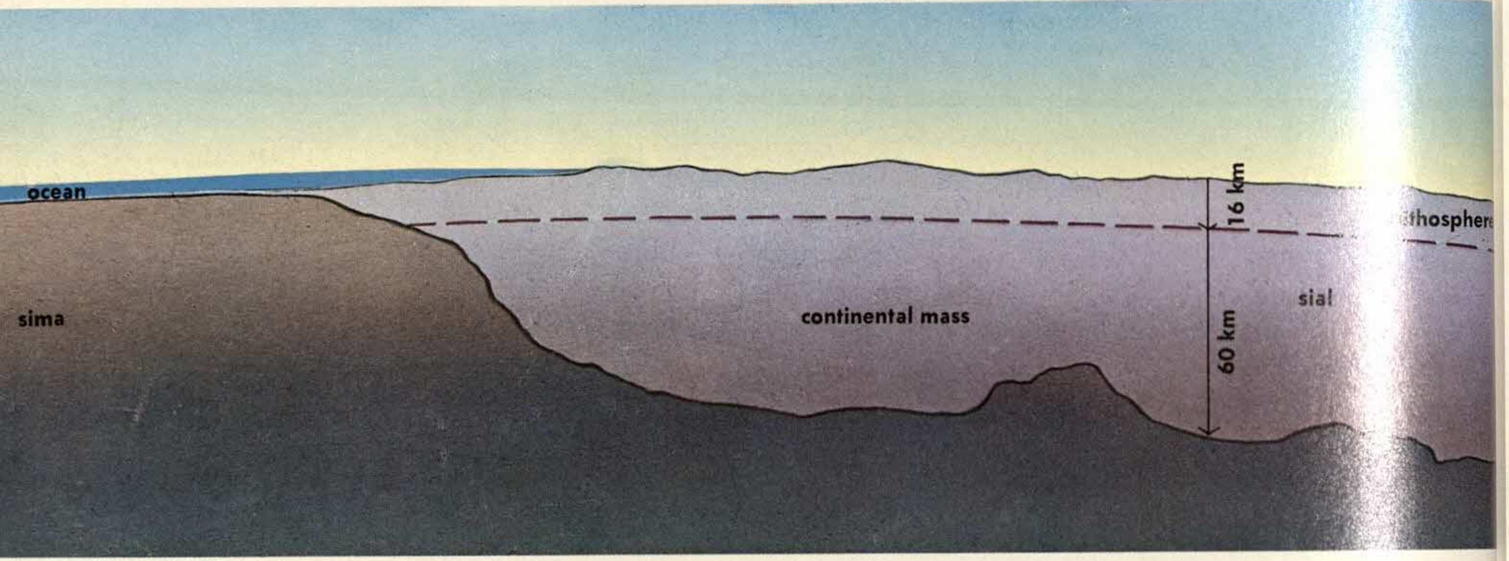
These rarer elements, which have not been found on Earth, are probably also absent from stellar and solar matter, where they have never been observed.

OXYGEN: A VOLUMINOUS ELEMENT

The atoms of the different elements vary greatly in volume. For example, if atoms are imagined as small spheres, those of oxygen and potassium would have a diameter more than three times that of silicon, and almost twice that of magnesium. The volume of a sphere is proportional to the cube of its diameter; therefore, oxygen atoms are about 30 times more voluminous than those of silicon, and 10 times those of magnesium. The table of abundance by volume of the more important elements in the lithosphere shows that oxygen, which makes up almost half the weight of the lithosphere, takes up almost 92 percent of the space.

ELEMENTS IN THE LITHOSPHERE—The percentage by volume of the elements in the lithosphere is shown in a stereograph.





PROFILE OF THE EARTH'S CRUST—The Earth's crust (sial) extends to an average depth of 60 km (about 37 mi) beneath the continental masses. Beneath the oceans, the rock mantle (sima) is reached almost immediately. The lithosphere is that part of the crust from the surface to a depth of 16 km (about 10 mi). Seismic waves show that the internal composition of the Earth is not uniform; it is subdivided into many strata. The Earth's interior is shown in a single color, reflecting the incomplete knowledge of the characteristics of these strata.

ABUNDANCE OF ELEMENTS IN THE LITHOSPHERE

Element	*Ionic radius (Goldschmidt) in Ångstroms*	*Percentage by volume*
oxygen	1.32	91.97
silicon	0.39	0.80
aluminum	0.57	0.77
iron	0.82	0.68
magnesium	0.78	0.56
calcium	1.06	1.48
sodium	0.98	1.60
potassium	1.33	2.14

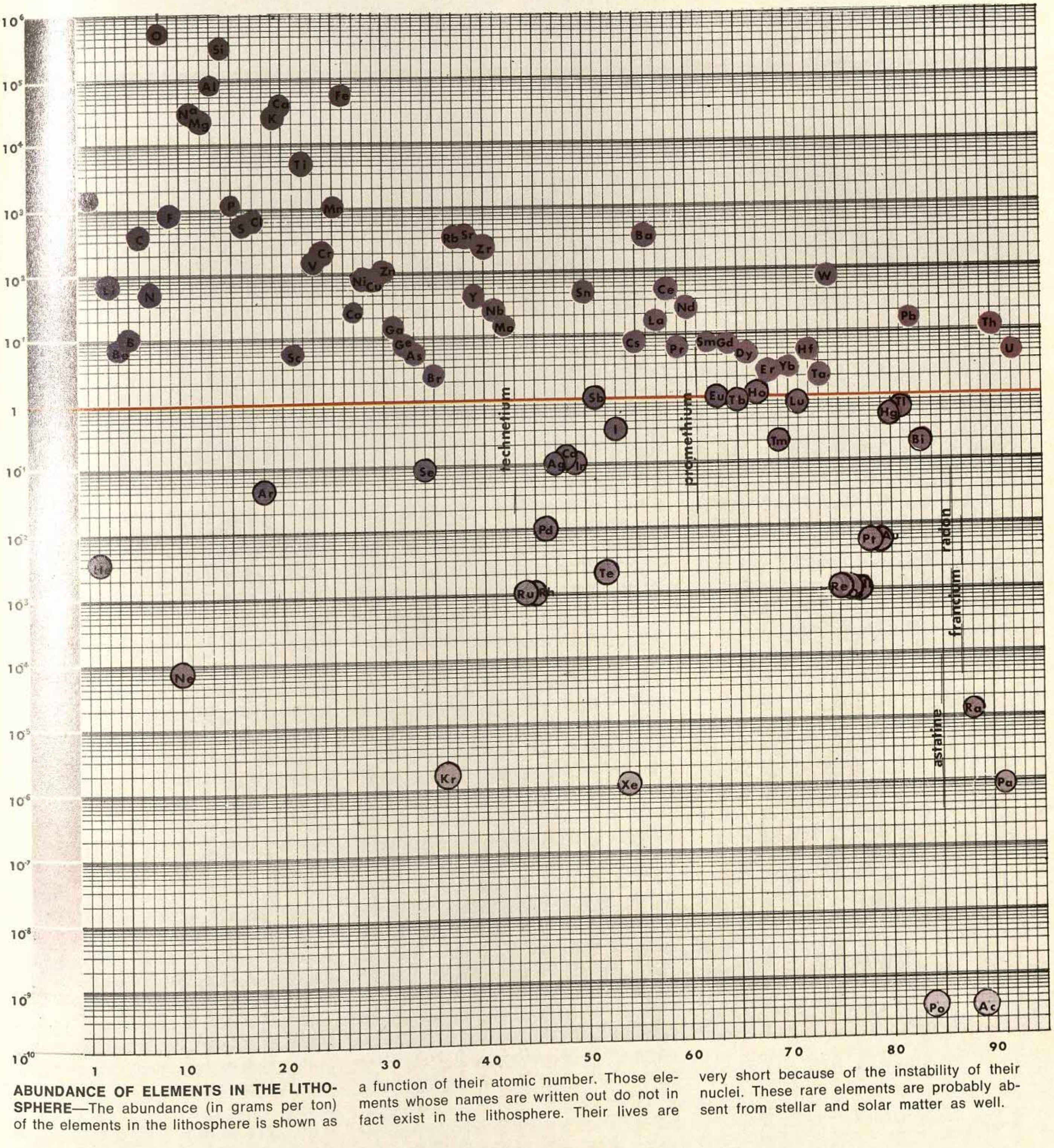
To understand how it is possible for oxygen to occupy such a large part of the lithosphere, the atomic structure of the compounds in the Earth's crust must be considered. For example, quartz (SiO_2, silicon dioxide) contains two oxygen atoms for each atom of silicon. If the atoms are again thought of as small spheres placed one on top of the other to form a regular network, the silicon atom is very small compared with the two large oxygen atoms. Other common substances—iron oxide, calcium carbonate, aluminum compounds—with rare exceptions have oxygen comprising the larger part of their volume.

THE GEOCHEMICAL CYCLE

Many geochemical processes in the upper lithosphere affect its chemical composition. All matter on the Earth's surface and in the uppermost parts of the lithosphere are involved in a slow, complicated cycle that causes changes in the structure and chemical composition of rocks. New rocks with new properties result. Some changes are caused by outside forces; others are confined mostly to upper levels of the lithosphere.

In the geochemical cycle, an igneous rock, for example, that is exposed at the surface will be weathered by running water, wind, and ice. The rock gradually crumbles and dissolves over the span of many millions of years. Some minerals, such as quartz, are carried away by rivers to become sands. Other minerals, such as amphiboles, micas, and feldspars, decay partially and combine with water to become clay minerals and clay muds that form sediments on the sea floor.

Over millions of years, these sediments are buried to depths of several miles; and, gradually, they are compacted into shales and sandstones. Finally, they are squeezed and heated to become slates and quartzites at depths of more than five miles down in the Earth's crust. If high pressures and high temperatures continue, these rocks change further; new minerals form by means of chemical changes, and the rocks become metamorphic schists and gneisses. At still greater depths, these rocks may finally melt, becoming igneous rocks. Eventually, the igneous rocks push their way upward through cracks into the crust to points near the surface where they solidify. Finally, when the surface rock which lies above these newly solidified igneous rocks is weathered down deeply enough, the new igneous rock becomes exposed at the surface. Weathering begins again to decompose it, and the cycle is completed, only to start all over.



ABUNDANCE OF ELEMENTS IN THE LITHOSPHERE—The abundance (in grams per ton) of the elements in the lithosphere is shown as a function of their atomic number. Those elements whose names are written out do not in fact exist in the lithosphere. Their lives are very short because of the instability of their nuclei. These rare elements are probably absent from stellar and solar matter as well.

TERRESTRIAL HEAT | a wide range of temperature

The temperature at the surface of the Earth ranges from about 80° C (112° F) below zero at the South Pole to about 50° C (122° F) above zero at the equator. Moreover, in any one locality the temperature is not constant but varies from day to night, with the change of the seasons, and with meteorological events.

SOLAR HEAT

If the sun were at the center of an enormous sphere that had a radius equal to the distance between the sun and the Earth, every square meter of this sphere would receive 100 calories of heat per second from the sun. If the Earth's atmosphere were absolutely transparent to solar radiation, this amount of heat would reach the ground in the tropics at midday, when the sun is at its zenith.

With the exception of nuclear energy, all the energy used on Earth is derived from the sun. A long time ago the fossil fuels—whether solid (coal), liquid (oil), or gas (methane)—were formed from solar energy. When these fuels are burned in the oxygen of the air, only a small part of the solar energy that formed the fuels is recovered.

Hydroelectric energy is simply solar energy that has evaporated seawater. When this moisture falls again on the mountains, it accumulates an energy potential as gravity pulls it to a lower level.

In one year, solar radiation supplies 10^{24} calories of heat to the Earth. Disregarding the heat reflected back into space by the Earth's atmosphere, 85 percent of this heat is dissipated in the evaporation of seawater and 15 percent in heating the soil. Only 0.1 percent is used in the photosynthesis of plants.

HEAT OF THE EARTH'S INTERIOR

Thirty m (about 100 ft) below the surface of the Earth, the temperature remains practically constant at all times. This temperature is very near the average surface temperature of the same locality. Since solar radiation in a given season is barely enough to heat the crust of the Earth a few degrees, a depth of 30 m is sufficient to protect the bedrock from the fluctuations of solar heat. Moreover, during the night a part of the Earth's surface heat is dissipated and lost. In the latitudes of the temperate zones, as in Europe, summer temperatures on the surface sometimes reach 30° C (86° F), and in winter −10° C (about 14° F); yet the temperature of the subsoil at a depth of 30 m remains constant at about 10° C (50° F). A large part of the materials of the Earth act as a perfect thermal insulator.

The temperature rises at greater depths, but the rise is not uniform. Near recent volcanic eruptions, for example, the rise is much higher than in most other areas. The average increase is 1 C° (1.8 F°) for every 100 m. If this proportionate rise continued, the temperature at the core of the Earth would be extremely high: at a depth of 50 km (about 30 mi) beneath the crust, this temperature would be 1,000° C (1,832° F), which is very close to the actual temperature. Partly because of the great pressure at this depth, the melting point of rock is much higher than at the surface. Even at 1,000° C, however, the rocks are not molten, but are soft and viscous.

Scientists estimate that temperatures deeper inside the Earth are relatively low. Despite the great pressures, the temperature is unlikely to be as high as 10,000° C at a depth of 500 km (about 300 mi). At such a high temperature, the rocks of the mantle would be completely fused; experimental analysis of the propagation of transverse seismic waves has shown that the temperature of these rocks is below the melting point. The study of seismic waves also confirms that the temperature cannot be 100,000° C at the core of the Earth, a depth of 5,000 km (about 3,000 mi), but is estimated at about 4,000° C (about 7,232° F). The study of the structure of the inner core of the Earth indicates that the temperature continues to rise by 1 C° every 50 m (1.8 F° every 160 ft to a depth of 20 to 30 km (about 12 to 19 mi), and then levels off.

THE ORIGIN OF TERRESTRIAL HEAT

Since the surface of the Earth is cooler than the interior and the temperature rises with increasing depth, heat must be propagated from the interior toward the exterior to disperse in the surrounding space. In a body having hotter and colder regions, heat is always radiated from the hotter to the colder parts. From their knowledge of the conductivity of rocks and the variation of temperatures in the surface layers of the Earth, scientists have calculated that from every square centimeter of the Earth's surface, 1.2 million gram-calories are lost per second. This small amount, multiplied by the area of the Earth, yields over 6 billion g-cal per second, or about 2×10^{20} g-cal per year.

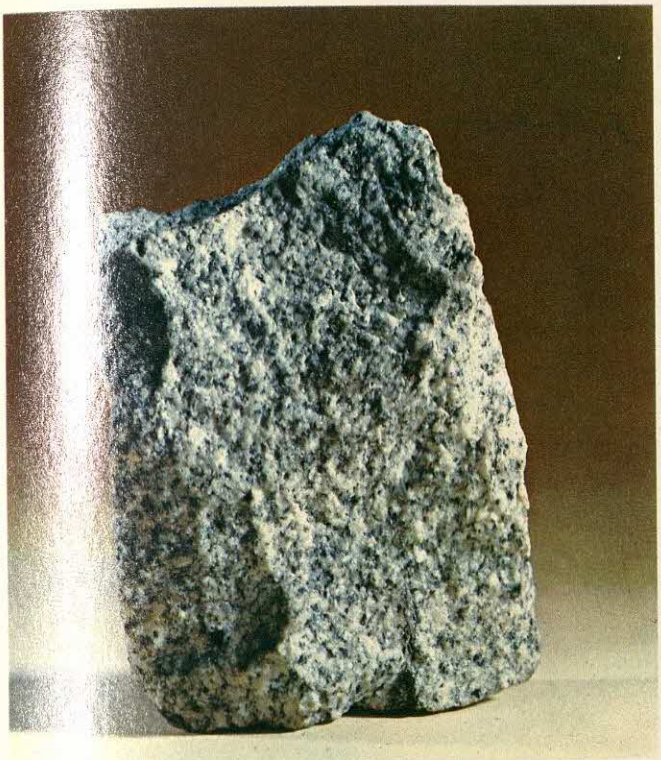
If the Earth continues to give off 2×10^{20} g-cal each year for a billion years, the internal temperatures of the Earth will drop by 22° C (40° F) in the same period of time. The present rate of heat loss is too slow to explain how the Earth has cooled off by thousands of degrees since its formation.

The heat given off by the Earth may be derived either from reserves or from a source constantly generating heat. Heat that came from reserves would have been inside the Earth from the time when the Earth was formed. Fuels, reactions, or phenomena that generate heat would account for the quantity of heat that continuously flows from the Earth.

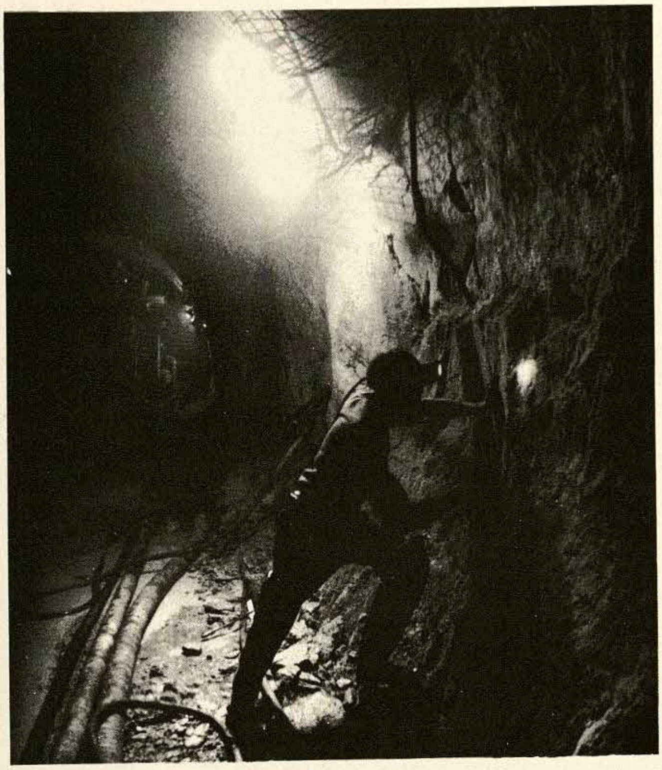
The hypothesis of residual heat can probably be dismissed. If this hypothesis were valid, the internal temperature of the Earth would be much greater than it is and would continually increase toward the core. Heat dissipation from the surface would also be considerably greater. Instead, the Earth can be compared to a large sphere wrapped in a heating pad that maintains a more or less constant temperature.

HEAT FROM RADIOACTIVITY

The lithosphere, or crust of the Earth, has a mass of about 2×10^{19} tons. The



HEAT GENERATORS—Rocks such as granite, which compose the greater part of the lithosphere, contain the elements radium, thorium, and potassium. The radioactive nuclei of these elements are responsible for the thermal fluctuation of the Earth's surface.



HEAT AND DEPTH—As depth increases, the heat of the Earth increases. This phenomenon is clearly perceived by those who work in mines or who excavate tunnels, where temperature rises about 1 C° (1.8 F°) for every 30 to 50 m (about 100 to 160 ft) of depth.

lithosphere contains four parts per million by weight of the radioactive element uranium and 12 parts per million of the radioactive element thorium, or a little less than 10^{14} tons of uranium and about three times as much thorium.

The atoms of these two radioactive minerals emit radiations as the atoms disintegrate at a slow, continuous rate. The energy of the radiations (alpha, beta, and gamma rays) is absorbed by the rocks that contain them and is transformed into heat. Furthermore, when an atom of uranium or thorium disintegrates, an atom of another substance is produced, also radioactive, that sooner or later also breaks down and releases more heat. Nuclear physicists have studied the entire series of nuclei produced when a nucleus of uranium or thorium disintegrates and is transformed. Before the disintegration chain ends with a stable nucleus, about 10 nuclei have emitted radiations and have produced heat.

Series of nuclei that succeed each other from the primary elements (uranium and thorium) until the stable end product is reached are called radioactive families. Potassium, rubidium, and samarium, which are also found in nature, are also radioactive. Other atoms that undergo a succession of radioactive transformations are created artificially in the laboratory.

Nuclear physicists can estimate how much heat is produced at any one time by a gram of each primary element of each radioactive family at any or all stages in its transformation. For example, 1 g of uranium, together with its disintegration products, emits about 0.75 cal per year; thorium produces 0.20 cal, and potassium, 0.000027 cal. If a gram of uranium could be thermally isolated, the heat produced in a year would not be sufficient to raise the temperature of a gram of water by 1 C°.

When the heat supplied by the decay of such minor atomic nuclei as rubidium and samarium is taken into account, the radioactive constituents of the rocks in the entire lithosphere yield some 10^{20} cal a year. The lithosphere constitutes only 4 percent of the Earth's volume. Nevertheless, the heat produced in the lithosphere by the disintegration of radioactive elements is equivalent to half of all the heat that reaches the surface of the Earth from the interior.

The simple conclusion can be drawn that the radioactive elements present in the lithosphere explain the heat at the interior of the Earth, which has cooled in past ages from a temperature in the region of thousands of degrees to the present level. When the planet was hot, the heat supplied by the radioactive elements was very little compared with that dispersed from its reserves. When this temperature had dropped to its present level, radioactivity became the primary source of terrestrial heat.

HEAT FROM ROCKS

The distribution of radioactive constituents in rocks varies greatly. A ton of granite, one of the rocks richest in terms of radioactivity, yields 6.6 cal a year. A ton of dunite produces only one tenth of a calorie. Obviously, as the process of disintegration continues, all the radio-

THE MAXIMUM GRADIENT — Around lava flows, the Earth's temperature rises sharply. In some zones the rise is 1 C° for every 7 m (about 23 ft) of depth. The temperature of molten lava reaching the Earth's surface ranges from 700° to 1,200° C (1,300° to 2,200° F).

active nuclei will gradually give off less energy and will eventually disappear. By analogy, radioactive decay must formerly have been greater than it is today, when uranium and thorium are the two main heat-producing elements. After 4.5 billion years, the uranium now present in rocks will disintegrate at half its present rate of decay. More than 10 billion years will pass before the decay of thorium is reduced accordingly. Thus, about 4.5 billion years ago, the radioactivity of uranium was double that of today, while about 14 billion years ago the radioactivity of thorium was double that of today.

Some billion years ago, the production of twice as much heat as today may have affected the temperature of the ancient lithosphere. Greater volcanic activity and more intense orogenesis may have been caused by this intense heat. These phenomena require more detailed study.

Rocks characteristic of the mantle, such as dunite, contain few radioactive constituents. The assumption can be made that no radioactive elements exist underneath the lithosphere. Radioactive elements in the depths, distributed as abundantly as on the surface of the Earth, would radiate so much heat that the Earth would have remained much hotter than it is today. Scientists have amassed considerable evidence to show that the temperature of the Earth is not rising at the present time. Its heat apparently is produced almost entirely in the lithosphere. Through some elaborate process, a state of equilibrium seems to have been reached.

It was believed for a long time that if most of the radioactive material is in the crust, which is thick under the continents but thin or almost absent under the oceans, then most of the heat flow would take place in continental areas. Heat-flow measurements on the ocean bottom have shown that this view is erroneous; the radioactive material is there, but under the oceans it seems to be in the mantle below the Mohorovicic discontinuity and not in the crust.

THE ISOSTATIC THEORY | equilibrium and compensation

ICEBERGS AND MOUNTAINS—On occasion, mountains have been compared with icebergs. An iceberg floats in the sea because the seawater is denser than the material of the iceberg. Somewhat similarly, the rocks constituting the Earth's crust float on a mantle of denser rocks. Only one ninth of the total volume of an iceberg projects above the surface of the sea; the remaining nine tenths lies hidden beneath the water. Similarly, the rocky mass of a mountain is all that is visible, but the roots of the mountain extend downward for some distance into the interior of the Earth.

2

AERIAL VIEW OF MOUNT CHIMBORAZO— Near this massive mountain, Pierre Bouguer discovered anomalies or irregularities in the values of the force of gravity that he was measuring. To explain these anomalies, geodesists first thought—mistakenly—that the mountains were full of caves that descended to great depths.

The geologic hypothesis of isostasy suggests that, at a certain depth within the Earth's crust, rocks are under equal pressure. This implies that the average density of rocks beneath mountains is less than the average density of rocks underlying the oceans. In other words, the amount of matter extending above sea level exactly balances or offsets any deficiency of matter below sea level. The term isostasy derives from two words, *isos* (equal) and *stasis* (condition) and refers to this hypothetical state of equilibrium. The principle of isostasy was first suggested by the great Leonardo da Vinci.

In 1738 Pierre Bouguer, a French scientist, arrived in South America to conduct geodetic surveys. He was particularly interested in measuring the arc of the meridian near the equator. In the course of his investigations, Bouguer attempted to calculate the force of attraction exerted by a mountain mass on a nearby body. He decided to determine how much a large mountain (Mount Chimborazo, Ecuador) deflected a plumb line from the vertical. Much to his amazement, Bouguer discovered that the plumb line, instead of being attracted by the mountain mass, actually was repelled—as though the mountain were a hollow dome covering a deep abyss that extended far below sea level. The only explanation offered at the time suggested that mountains near which the plumb-line measurements were made must be riddled with enormous caverns descending to great depths. However, no convincing theory could be advanced to explain the phenomenon.

ISOSTASY AND AIRY'S HYPOTHESIS

Bouguer's results were far from accurate; however, they did awaken interest in this method of investigation. In 1774, for example, a similar method was used to measure the plumb-line deflections near a mountain in Scotland. Then, in 1855, G. B. Airy, a British astronomer, utilized a modified version of Bouguer's method to conduct experiments in the Himalayas. He, too, was struck by the apparent rarefaction of matter.

The phenomena observed by Bouguer and Airy can be explained by the hypothesis of isostatic equilibrium, which states that the rocks of the Earth's crust differ in density from those of the mantle; the crust "floats" on the denser, but more plastic, rocks of the mantle. Where great ocean depths occur, the crust of light rocks is presumed to be thin or nonexistent; where continental masses exist, this crust is presumed to be quite thick.

Airy hypothesized that large mountains consist of rocks much lighter than those of the plastically deformable substratum on which they rest. The resulting phenomenon is similar to that of an iceberg, in which part of the iceberg's mass projects above the surface of the sea; that is, ice is less dense than water and is, therefore, supported by the water. The ratio of the volumes of the submerged portion and the portion above water can be calculated with great accuracy if the density of the ice and the seawater are known. (The volume of the submerged part is approximately nine times the volume of the part above-water.)

Airy reasoned that, given the densities of both the rocks forming the mountain and those forming its substratum, it would be possible to calculate the depths of the "roots" of a mountain of known height. The rocks of a mountain 3,000 m (about 10,000 ft) high, therefore, must descend more than 33 km (about 21 mi). These calculations are not completely accurate, however, because they do not take into account the fact that the rocks may vary in composition and density before reaching this depth. Airy's theory assumed that the density of the rocks is constant.

PRATT'S HYPOTHESIS

Research into the irregularities of gravitational attraction, especially those discovered near mountain systems and great marine basins, led the British astronomer J. H. Pratt to a modification of Airy's hypothesis. Pratt held that all gravitational irregularities observed at the Earth's surface decrease and vanish deep in the stratum of rocks that emerges at the surface. According to Pratt, the crustal density varied inversely as the height of the topography. Mountain areas, he suggested, were less dense than lowlands.

The Pratt and Airy hypotheses were then developed further by the American geodesists, J. F. Hayford and William Bowie. These men proposed that isostatic equilibrium is attained beneath the Earth's surface at a depth of not more than about 100 km (about 62 mi), and that this equilibrium has been preserved throughout the entire period of the evolution of the Earth's crust. They contended that every topographic feature on the Earth's surface is compensated completely and locally.

Later, as scientists acquired more knowledge of the Earth's crustal evolution, they came to agree that isostatic compensation is regional rather than local. A mountain, for example, has a horizontal as well as a vertical isostatic effect. In other words, the excess of mass of the mountain is only partially compensated by the light root of the mountain; some isostatic compensation occurs over a rather large area, perhaps covering several thousand square kilometers. Recent studies indicate that at least 85 percent of the excess mass of mountains and the deficiency of mass of the oceans is isostatically compensated.

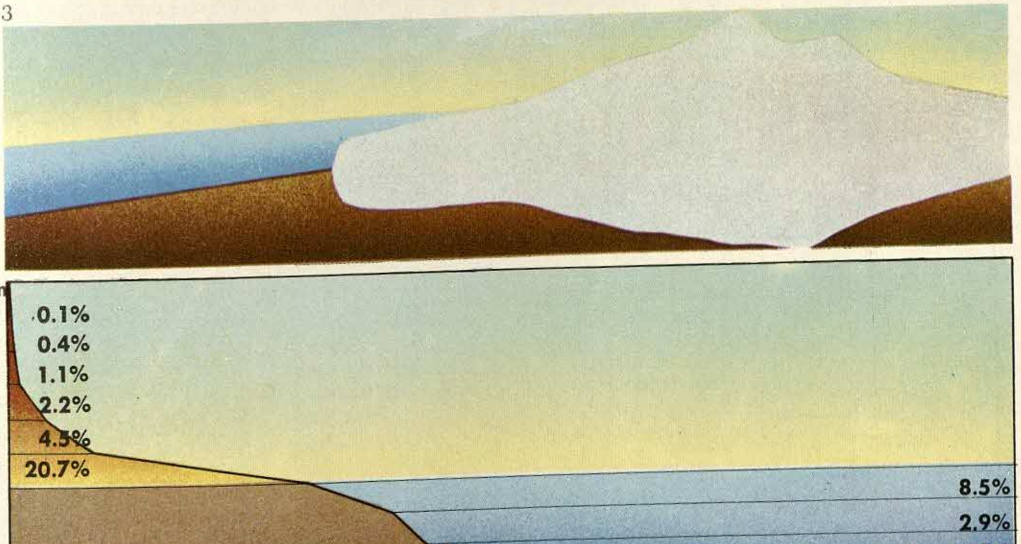
PROOF OF THE ISOSTATIC THEORY

The isostatic theory can be tested through increasingly accurate measurements of gravitational irregularities, measurements involving the use of instruments such as gravimeters and through modern techniques derived from progress in satellite studies. Measurements taken near the Earth's surface are strongly affected by disturbing factors present in space. Therefore, artificial satellites have been used to help determine gravitational irregularities. If the Earth's crust were perfectly homogeneous and of uniform thickness,

AIRY'S THEORY — The British astronomer G. B. Airy proposed that the higher a mountain is, the deeper its roots are sunk into the viscous matter below the surface crust (Illustration 3).

THE HYPSOGRAPHIC CURVE — This graphic presentation (Illustration 4) shows the percentages of the Earth's crust at different elevations, ranging from land extending over 5 km (about 3 mi) above sea level to the floor of oceanic trenches more than 7 km (about 4.3 mi) below sea level. Most land lies less than 1 km (about 0.6 mi) above sea level. The submerged peripheral edges of the continents (the continental shelves or platforms) extend for the most part to a depth of about 1 km below sea level, where the ocean floor plunges to a depth of 4 to 5 km (about 2.5 to 3 mi). Much of the sea floor is located at this depth.

3



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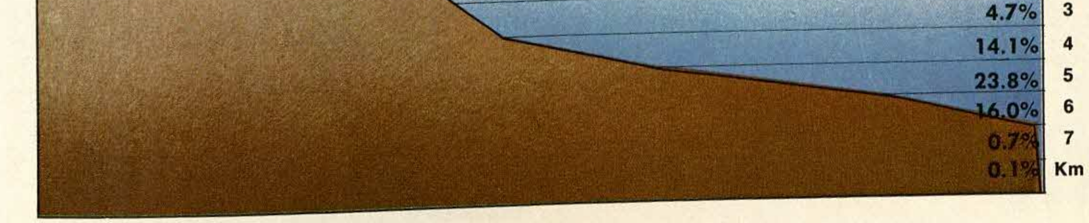


a satellite would orbit the Earth in a perfect ellipse. Due to gravitational irregularities, however, the satellite oscillates around its mean orbit; filmed records of the amplitude of the oscillations permit the extent of gravitational irregularities to be measured.

The movement of artificial satellites can be captured on film by special cameras—the colossal Baker super-Schmidt cine-theodolites. Deviations from predicted orbits provide data for calculations of the extent of gravitational anomalies or irregularities. Any satellite is suitable for these experiments, provided that it does not orbit at too great an altitude, because it does not need to carry special instruments; it needs only to be visible through the cine-theodolites.

Seismic waves originating from earthquakes are also useful in verifying the isostatic theory. These waves are reflected at the surface of discontinuity due to the change of density at the point where the crust and mantle meet. Artificial earthquakes produced by underground explosions can also create seismic waves, although the waves from such an explosion are not as strong as those produced by a strong natural earthquake. Nevertheless, artificial earthquakes have the advantage that they can be made to originate at the point and moment desired. Study of rock layers through the use of man-made earthquakes is significant in the search for mineral deposits; the technique is known as seismic prospecting. Using this technique, scientists have measured the thickness of the Earth's crust at many points.

THE STRUCTURE OF THE EARTH'S CRUST

Seismic determinations and calculation of isostatic equilibrium have shown that the thickness of the Earth's crust beneath the continents averages about 30-60 km (about 19-38 mi), while beneath the cover of oceanic waters the crust is only a few kilometers thick—about 10 at the most. Below this granitic crustal cover lie the more basic rocks of the mantle.

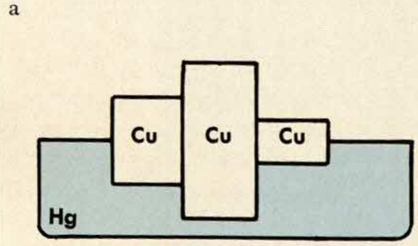
Some scientists have calculated that the continental blocks (including the continental shelves) constitute about 60 percent of the total mass of the crust; the part of the crust underlying the great oceans comprises about 30 percent of the total.

The crust of the Earth is a continuous, but not uniformly thick layer of rock covering the mantle. The continents may be thought of as "islands" floating on the surface of the sima. Through the course of the Earth's history, numerous isostatic compensations or adjustments have occurred, with parts of the crust at times sinking and at other times rising.

If an iceberg were weighted with heavy ballast, it would sink until the displacement of additional water compensated for the added weight, in accordance with Archimedes' principle of buoyancy. Twenty thousand years ago Scandinavia was weighted down with an ice cap from the last "Ice Age." The entire peninsula was covered with a continuous sheet of ice about 2,000-3,000 m (about 1 to 1.8 mi) thick. Later, most of this ice melted. Relieved of this great weight the Scandinavian peninsula has already risen about 300 m (about 0.18 mi). The rise is slow because the peninsula rests on rocks rather than on liquid. These rocks react in the manner of a plastic material, becoming deformed under the downward pressure of the overlying matter. (A liquid would react instantaneously.) The Scandinavian peninsula will probably continue to rise slowly during the next few centuries.

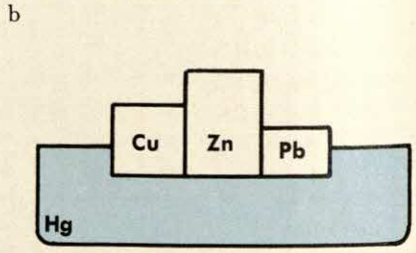
The great viscosity of the Earth's materials makes isostatic adjustment a slow process. Recoil in the glaciated tract of Europe continues although the icecap began to melt away 40,000 years ago and although it had only 1 percent of its original weight 7,000 years ago. Time lag in the adjustment for any transfer of surface load and the strength of the lithosphere are two causes for some imperfection of isostatic balancing; investigators believe that a small degree of strength characterizing the asthenosphere is a third cause. The asthenosphere is a zone from 30 to 75 mi down that is supposed to be the site of the isostatic balancing pressure.

5



AN EXAMPLE OF ISOSTASY—Illustration 5a shows three copper blocks floating at different heights in a bowl of mercury. The longer the block, the more it extends above (and below) the mercury surface. This illustrates Airy's hypothesis that mountains "float" on the denser rocks of the mantle and have "roots" in the mantle.

Illustration 5b shows three blocks (copper, zinc, and lead) of different densities floating at different heights. This illustrates Pratt's hypothesis that mountains are less dense than the adjacent lowlands.



OROGENY | the formation of mountain masses

1

← **AN ALPINE MASSIF**—Mountains with sharp peaks and valleys with steep slopes are characteristic reliefs formed in recent geologic time. Erosion of these features has scarcely begun (Illustration 1).

The erosive action of water is so great and so relentless that, unless it were checked or countered in some way, it would flatten the surface of the Earth in a relatively short period of time. The deep gash of the Grand Canyon in Arizona, for example, was carved out by water in slightly over 20 million years, and the chasm continues to deepen at the rate of slightly over a half inch every century.

Fortunately, a total leveling of the Earth's crust is impossible. Turbulent waters plunging from high elevations toward the sea cut into and destroy the lands they traverse. On flat terrain, water flows slowly and causes only slight erosion; however, if the land is uplifted, the once placid water changes character and cuts deeply into the riverbed. In ancient times, for example, the Colorado River flowed across a plane that was elevated only slightly above sea level; but when the plain was uplifted about 2,000 m (about 6,500 ft), the river eroded its bed and steadily cut deeper into the Earth's crust. Erosion, therefore, is a never-ending process simply because orogeny—the formation of mountain masses—serves to counteract the leveling effects of erosion by uplifting parts of the Earth's crust.

OROGENY IN THE PAST AND PRESENT

In the past, orogenic forces created great mountain chains. Some of these have been almost completely leveled by the agents of erosion. Others, still existing today, bear only slight resemblance to the massive structures that people think of as mountains; their jagged peaks have disappeared altogether, and their once-steep slopes are now gentle, rolling hills. The Urals in the Soviet Union and the Appalachians in the United States are examples of ancient ranges that were formed over 100 million years ago.

Many of the most impressive mountain ranges existing today are of more recent origin; indeed, some experts maintain that the Alps, the Himalayas, parts of the American ranges, and other chains are still rising. Their plunging valleys and towering peaks furnish sufficient evidence that these mountains were formed recently—that is, about 40 million years ago.

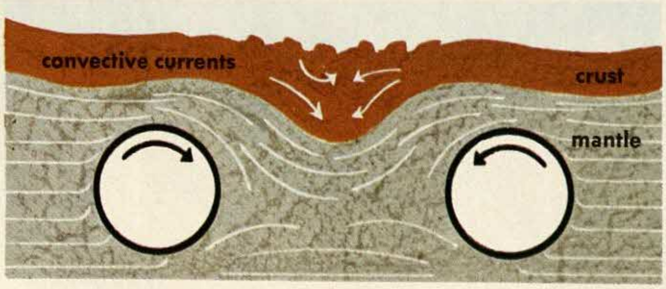
THE SUBCRUST CURRENTS

What are the factors underlying orogeny? According to the theory of isostasy, continental masses attain a state of equilibrium by rising from, or sinking into, the mantle of the Earth. It has been observed, for example, that the Scandinavian peninsula, relieved of the weight of the Quaternary glacial ice cap, is slowly rising. According to Archimedes' principle, this uplifting presupposes that mantle material is also rising with the Scandinavian continental mass and, therefore, is shifting vertically with it. The rising of the continental mass also assumes that the mantle on the rim of the mass is sliding toward that mass. If a floating body is pushed downward, it displaces the water below it toward the bottom, and it also displaces some of the water around its sides. Contrariwise, if the body is allowed to surface, the water rises from below it and rushes toward the body from the sides.

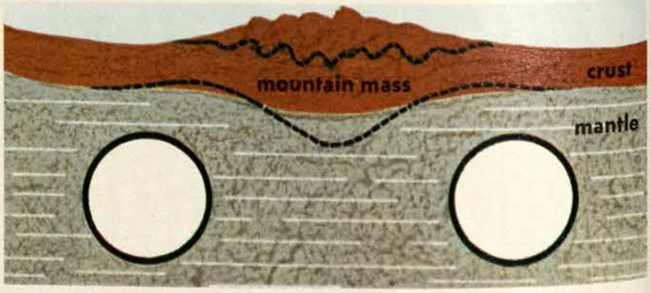
This signifies that movements of isostatic adjustment at the Earth's crust activate horizontal movements of the masses of the underlying mantle. Suppose that a light body is immersed in water and then allowed to come to the surface. The time required for the body to rise to the surface depends on the weight of the body, Archimedes' principle, the depth of the immersion, and the resistance of the water to the body. In the case of a continent rooted in the mantle, the length of

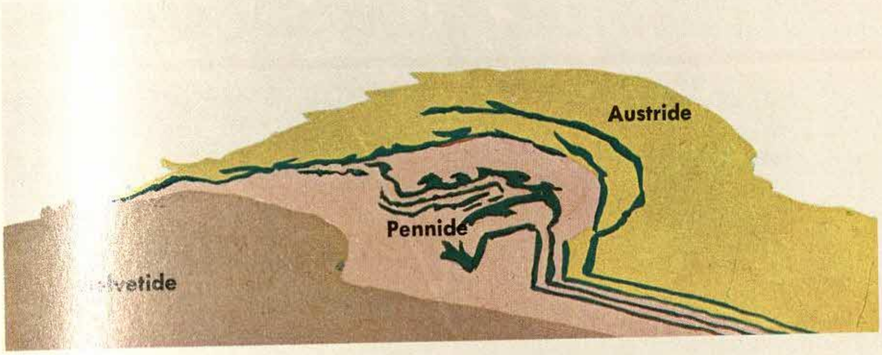
CONVECTIVE CURRENTS CAN GENERATE OROGENY—The rotation of rocky blocks immersed in the mantle causes convective currents on the surface. The crust, therefore, turns downward. More rapid movements create undulations on the surface of the crust (Illustration 2a). Once the convective movements cease, an isostatic equilibrium is reestablished through the uplifting of a corrugated mountain chain (Illustration 2b).

2a



2b





3

CROSS-SECTIONAL DIAGRAM OF THE WESTERN ALPS—This illustration shows that the rocks of the northern part of the Alps form a base over which the rocks moving from the south have traveled. A structural unit formed by the northern rocks and the foundation is called the Helvetide stratum, because of its geographical position. The southern rocks, on the other hand, form the so-called Austride stratum. The Austride rocky mass covers the entire Alpine massif; in the central part, instead of resting directly on the crystalline Helvetide rocks, the Austride rocks rest on the Pennide stratum.

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time necessary for it to rise or sink also depends on the viscosity of the mantle. The time required for a light body to rise to the surface of a highly viscous liquid, such as oil, depends mainly on the degree of the oil's viscosity. On the other hand, the viscosity of water is a negligible factor, having little or no effect on the time required for emergence. The viscosity of a substance decreases with increases in temperature. Now temperatures of about 1,000° C (1,832° F) are common at fairly shallow depths beneath the Earth's surface. Therefore, some of the rocks of the mantle are much less viscous than those in contact with the sial zone or outer crust. Indeed, at 1,000° C the viscosity of many rocks in the upper mantle drops to a level slightly higher than that of cold tar. A viscosity of this kind permits relatively rapid shifts of mantle masses under continental expanses. A shift of 10 cm (about 4 in.) per year is normal; more fluid rocks, however, may move at a faster pace.

THE THEORY OF CONVECTIVE CURRENTS

No experiments have been made to determine whether or not permanent convective currents exist in the zone beneath the Earth's crust; but, because the temperature of the mantle is not constant everywhere at the same depth, it is possible that temperature differences set the semifluid rocks into motion. This movement is analogous to the phenomenon of currents created in lakes and seas by temperature variations. Inside the Earth, these deep currents are thought to exert pressure on the crust masses, causing parts of the crust to rise or sink.

Other hypotheses have been advanced to explain the orogenic phenomenon, but none is so convincing as the theory of convective currents. The structure of the Alps furnishes evidence to support this theory; it is believed that convective currents provided the thrust that lifted these mountains above sea level. This majestic phenomenon no doubt had its origin in the northward movement of the African continent, just as, similarly, the Indian subcontinent's movement toward the north brought about the upward thrust of the Himalayas.

In conclusion, evidence exists to show that some crustal blocks are in motion. What causes these movements cannot be determined because they undoubtedly originate at depths that are presently inaccessible to exploration. In any event, it is extremely improbable that any factor other than the shifting of the mantle magma causes crustal movements.

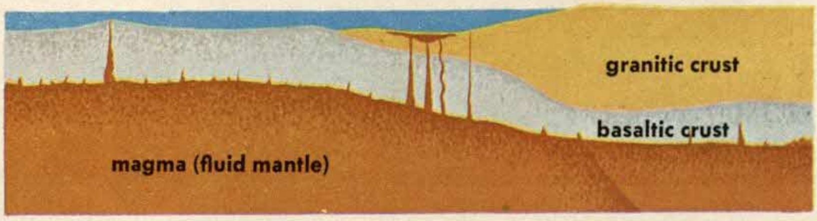
The orogenic hypothesis presented here is accepted today by many geologists. Other evidence may be found to prove that molten subterranean magmas move upward into crustal rocks and partially melt them with their intense heat. On occasion, these magmas even rise to the Earth's surface and produce volcanic phenomena that have resulted in the formation of many of the rocks on the Earth's surface. This orogenic hypothesis is known as accretion. It is likely that accretion, convection, and phase change all act together.

OTHER THEORIES

The phase change theory refers to a change in the crystalline structure of minerals, which may result from either temperature or pressure changes at the bottom of the Earth's crust. The tendency toward isostatic equilibrium might produce fairly large vertical displacements with the rise (from radioactive heating) and the subsequent fall in temperature in the lower boundary of the crust. While this theory alone might not explain mountain building, it can play an important subsidiary role in a complex and definitive theory.

Another agency held responsible for mountain building is not regarded as seriously as it once was. This is the theory of contraction. It can be described by the simile that the Earth resembles a shrunken apple, with the mountains and valleys constituting the wrinkles in the skin. Since the discovery of radioactive heating of the Earth, it has been hard to believe that the Earth has shrunk appreciably in geological times.

4a



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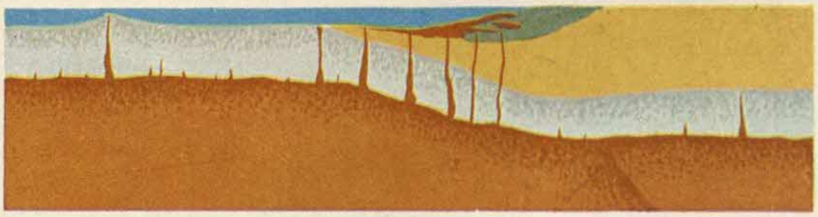

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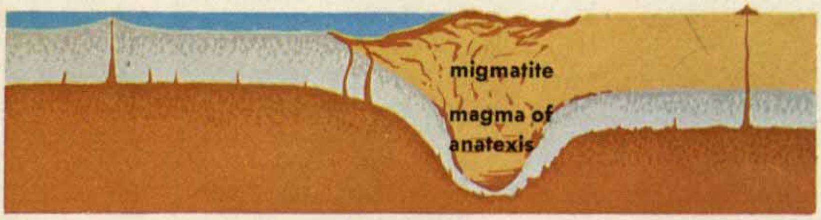
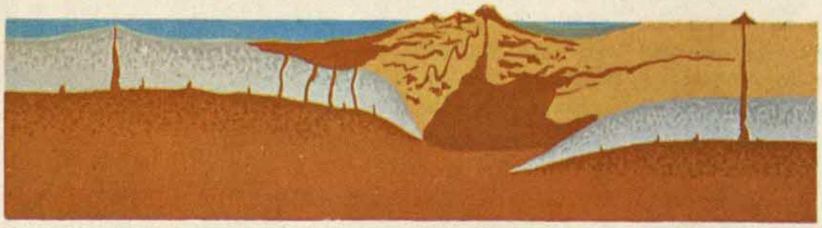


4d



THE PHASES OF AN OROGENIC CYCLE— These vertical sections of a region affected by orogenesis show the three fundamental elements that participate in the phenomenon: the continental granitic crust, the semirigid basaltic crust, and the fluid mantle or magma. In the first phase of an orogenic cycle (Illustration 4a), movement of a fluid mantle current toward the continental block provokes a fracturing of the rigid basaltic zone. A certain quantity of fluid mantle rises through the fissures, spreads over the surface of the marine bed, and partially fills in the depression at the rim of the continental block (the oceanic depression near the center of the illustration).

In the second phase of the cycle (Illustration 4b), the movement of the magma carries part of the rigid crust down with it, intensifies the fracturing, and causes a greater magmatic effusion on the surface of the seabed. Meanwhile, however, the erosion of the continent results in a partial filling of the ocean cavity with sediment. The strata of sediment deposited in the cavity form a geosyncline. The magma welling up onto the surface of the sea floor has to open its way through the thickness of these deposits also.

In the third phase (Illustration 4c), the fluid mantle current drags the rigid basaltic crust still farther down and bends its subcontinental stratum so that part of the continent sinks to a depth where it becomes partly fused to form the magma of anatexis. The chemical composition of this magma is that of the granitic rock of the continental block, eventually altered by a partial mixture with the underlying fluid mantle. The magma of anatexis penetrates the overlying rocks—which have been fragmented by the thrust and the resulting deformations—and forms a new kind of rock in which every fragmented part of the preexisting rock is cemented to the magma of anatexis that had invaded it. Before this rock solidifies, the invading magma clearly alters the composition of the invaded fragmented rock, which in turn modifies the composition of the invading magma. Rock formed by this process is called migmatite.

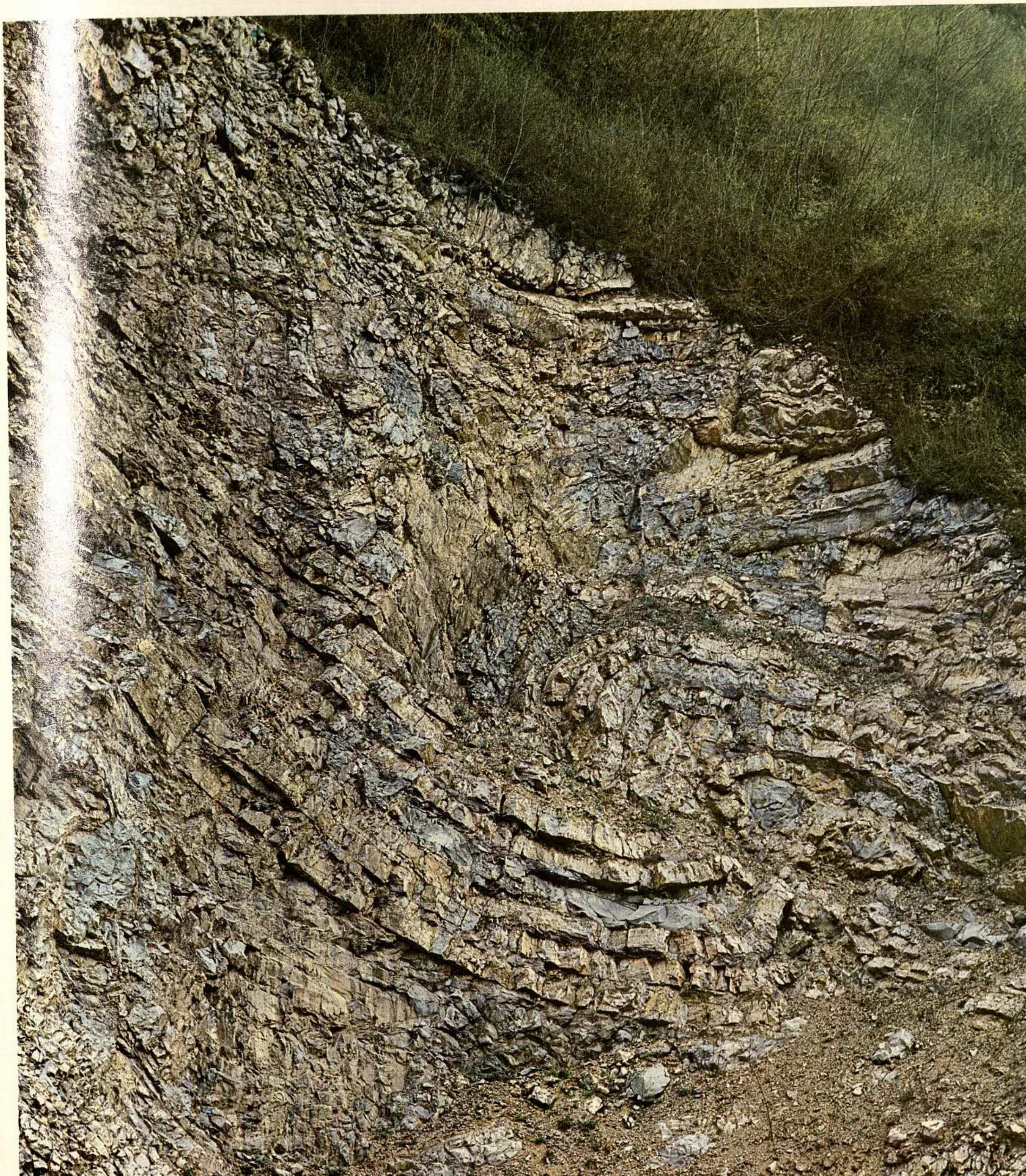
During this third phase, the continental block is isolated and subjected to the processes of fracturing and chemical alteration previously described. The rigid part of the basaltic crust bends with such intensity during this phase that it fractures part of the continental block. Thus, volcanic phenomena also occur within the continental massif.

During the last phase of an orogenic cycle (Illustration 4d), the entire system attains a state of equilibrium; that is, an adjustment takes place, lifting the granitic block that had been embedded in the rigid basaltic layer. This is the true orogenic phase, because it is the phase in which a part of the Earth's crust is raised. Other phenomena occur under the superficial strata. For example, the rocks remelted by the heat below may differ in density from the deep magmas with which they come in contact. Movements occur in the magma until the lighter rocks float on the denser rocks. These movements of magma, which is covered by fractured rocks of the granitic crust that was raised during the isostatic adjustment, often force the magma to the surface. Volcanoes, therefore, appear in the newly created mountains; this phenomenon, called orogenic vulcanism, lasts until these magmas (issuing from the remelted rock and lifted again by the isostatic adjustment) solidify.

THE ORIGIN OF EARTHQUAKES | mystery and theory

1

FAULT—This small fault shows the rock strata twisted, corresponding with the plane of movement. Sudden movement of rocks following the opening of such a fault may cause an earthquake. Faults have a wide range of sizes—from microscopic to hundreds of miles long.



Earthquakes are born in the depths of the Earth's crust and mantle. Because these regions are unknown and inaccessible, the nature of the forces that give rise to these phenomena is a matter of hypothesis.

The great fracture in the Earth's crust known as the San Andreas fault (in geological language, a fracture is called a "fault") is readily visible. Located along the western coast of the United States, it is among the largest known on Earth. In 1906, during the infamous San Francisco earthquake, the slippage of the ground along the sides of the fault was approximately 6 m (about 20 ft).

Generally, after a fault has made a sudden movement, the stresses in the ground decrease or disappear completely. Slippage stops and the fractured rocks lying along the fault settle down. But, although the earthquake stops, the forces pushing the Earth masses continue to exert pressure from both sides of the fault, and the rocky planes facing it sometimes continue to slip, releasing energy into the ground. Or the fault may become blocked, causing the surrounding area to undergo further distortion that culminates in another catastrophe.

The San Andreas fault is very old; its origin is not easily dated. In 1906, it made a great movement. But this was not the first movement made by this fault, nor will it be the last.

MINOR EARTHQUAKES

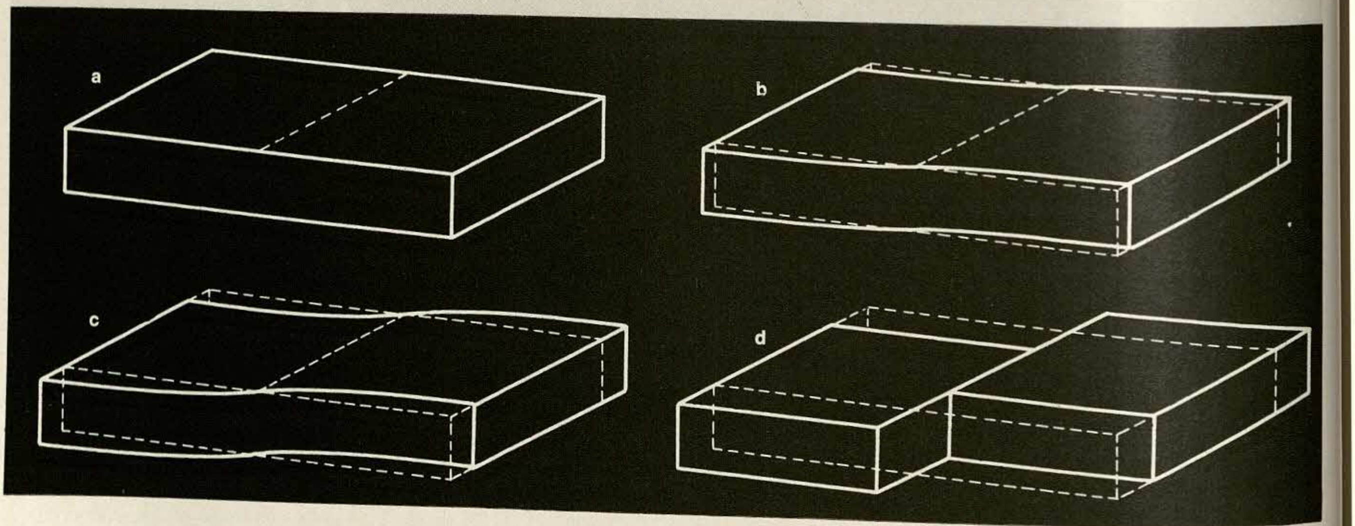
Fortunately, disastrous earthquakes of major proportions are relatively rare. But earthquakes of modest dimensions occur very frequently. The Earth never rests for an instant. Microearthquakes shake the Earth every day.

Some earthquakes are produced by the formation of small fractures. The waves of a stormy sea breaking on the coast may cause small vibrations (microseisms) that are nevertheless strong enough to be recorded by seismic stations located near the seacoast. Very strong winds may give rise to rapid variations in pressure that can cause weak, but detectable, seismic waves.

Violent noises, such as thunder or an explosion, can be passed on to the ground and broadcast as seismic waves. Sound waves created by large supersonic aircraft may cause weak shock waves when they reach the ground; these can be per-

THE SAN FRANCISCO EARTHQUAKE—The earthquake that destroyed much of San Francisco in 1906 originated on the surface. Traces of its causes can still be seen in the area. Because of the slow movements of the land lying under the coastal mountain chain in California, there was a progressive increase of stress in the rocks. The sketches illustrate the presence of tension in rocky terrain. About a century before the San Francisco earthquake, the area (shown here as a parallelepiped) was without stresses (Illustration 2a). Then the ground was subjected to pressures that distorted it (Illustration 2b). The tension and force exerted on the materials forming this rock mass were greatest along the midplane (Illustration 2c). The mass was increasingly distorted (strained), and, shortly before the earthquake occurred, the stress in the rocks reached such a pitch that the ground split along a straight line—the visible sign of a vertical plane along which the mass split in two. When there was no longer any cohesion between the various parts of the rock, the flexible distortion ended. The parallelepiped illustrates the split into two sections that no longer coincided (Illustration 2d). The movement of the rock masses, which suddenly lost their distortion and resumed the shape of a perfect parallelepiped, was transferred to the ground surrounding it in seismic waves.

2



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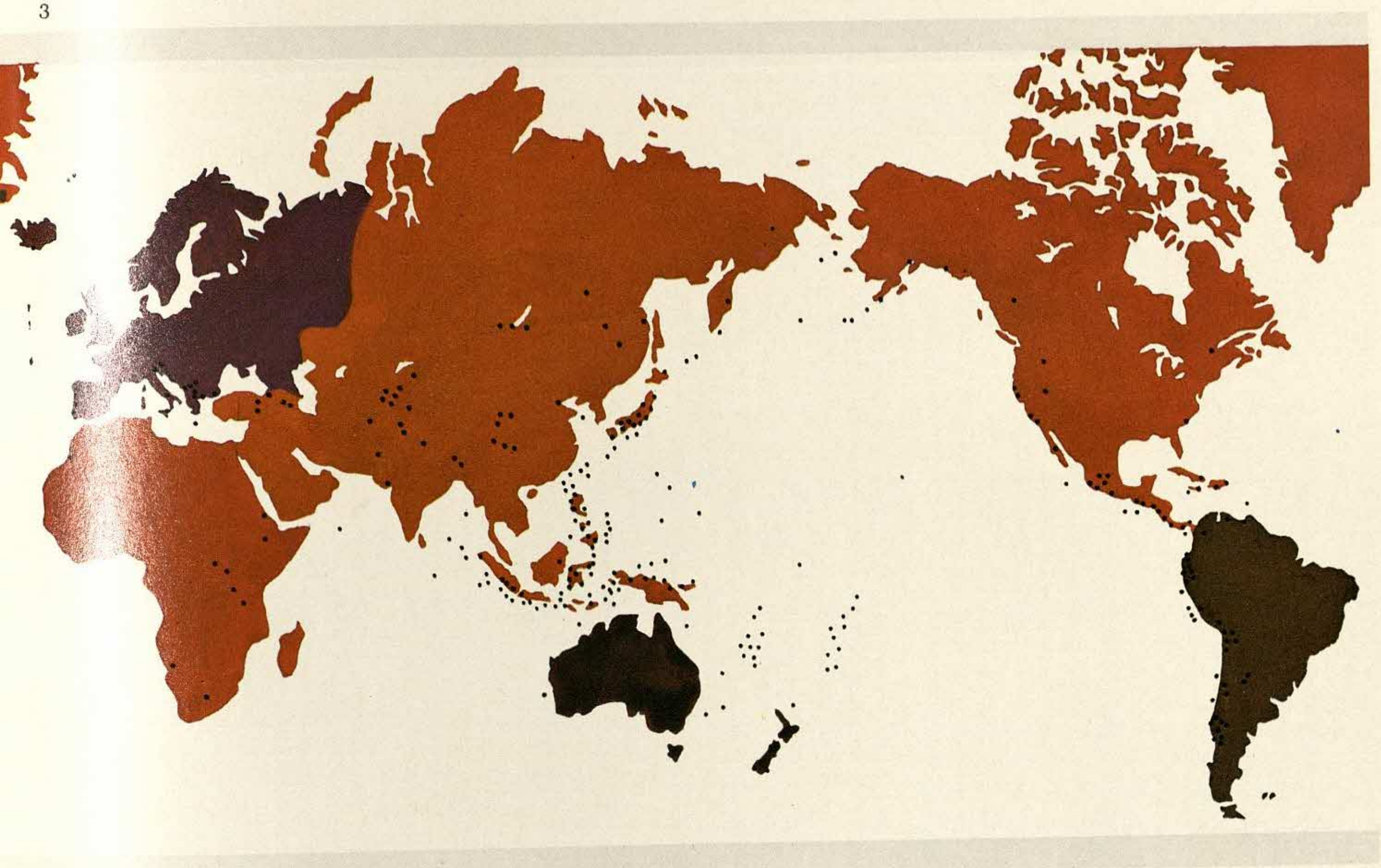


SEISMIC AREAS—Dots on the map marking major earthquakes that have struck the world within the past century or so indicate that some areas suffer more than others. Close study shows that seismic areas are concentrated where orogenesis is most intense. Among the areas of greatest seismic activity are: the Pacific Coast of the American continents along the lines of the great coastal mountain chains; the Mediterranean area with the mountain folds of the Atlas mountains, the Pyrenees, the Alps, and Anatolia; the great Asian mountain folds; the midline of the Atlantic chain or ridge; the area of mountainous folds in East Africa; the Pacific coastal strip stretching from the Bering Sea to Kamchatka, Korea, Japan, the Philippines, New Guinea, and New Zealand. The seismic areas in the Atlantic and Pacific oceans face deep oceanic depressions. The deep ocean basins and the continental shields have low seismic activity.

ceived tens of kilometers away.

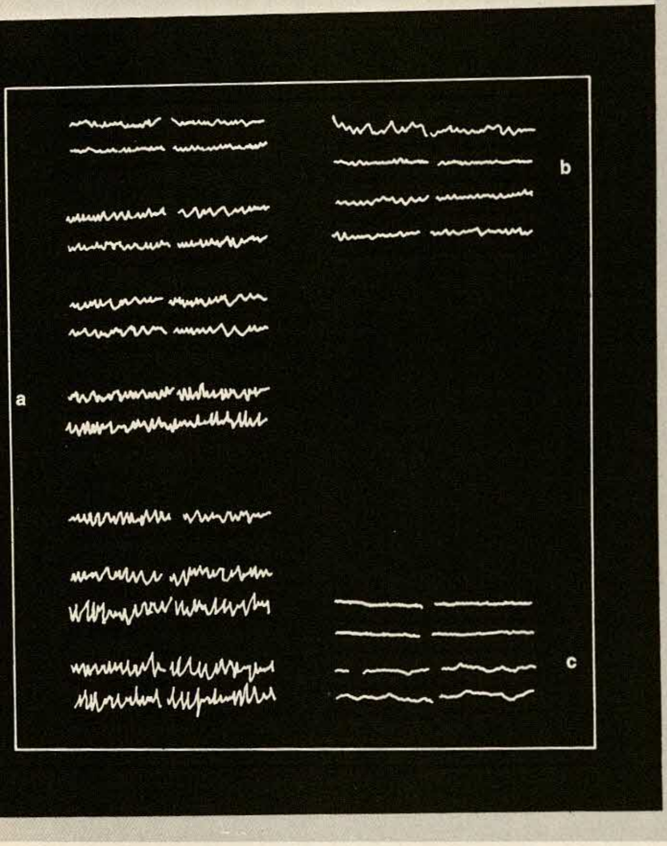
The explosion of large nuclear weapons produces shock waves great enough to be detected anywhere on Earth. Some seismographs are specially built to pick up the waves produced by these explosions, and many countries have monitoring systems set up to localize them.

Even some of man's constructive projects have been guilty of directly producing earthquakes. For example, when the basin of a large dam in the United States was filled for the first time, seismographs arranged around it detected a series of earthquake shocks whose epicenter was located in the proximity of the dam.

TECTONIC EARTHQUAKES

Sudden deformation of the earth releases stored elastic strain energy that has accumulated over a period of years or centuries. The most common earthquakes are caused by this release in the form of seismic waves that travel outward in all directions. Earthquakes of this type are known as tectonic earthquakes. The source region for the largest tectonic shocks can be as much as 2 million mi^3 in contrast to that for mild shocks of a fraction of a cubic mile. Such movements account for continental drift and the creation of ocean basins.

4



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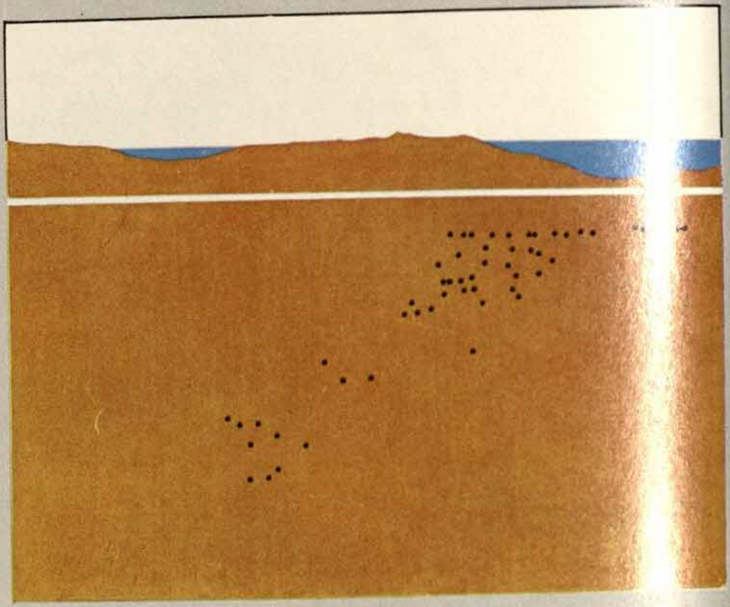


THE EARTH NEVER RESTS—Every day, the Earth is shaken by microseisms. These can only be detected through the use of very sensitive instruments. Some of these quakes are caused by the wind, others by waves of the sea, still others by similar mild shocks. The diagrams show seismograms for microearthquakes generated by gusts of wind. Illustration 4a shows gusts of the "bora" (a cold wind over the northern Adriatic), blowing east-northeast at speeds between 30 and 110 kmph.

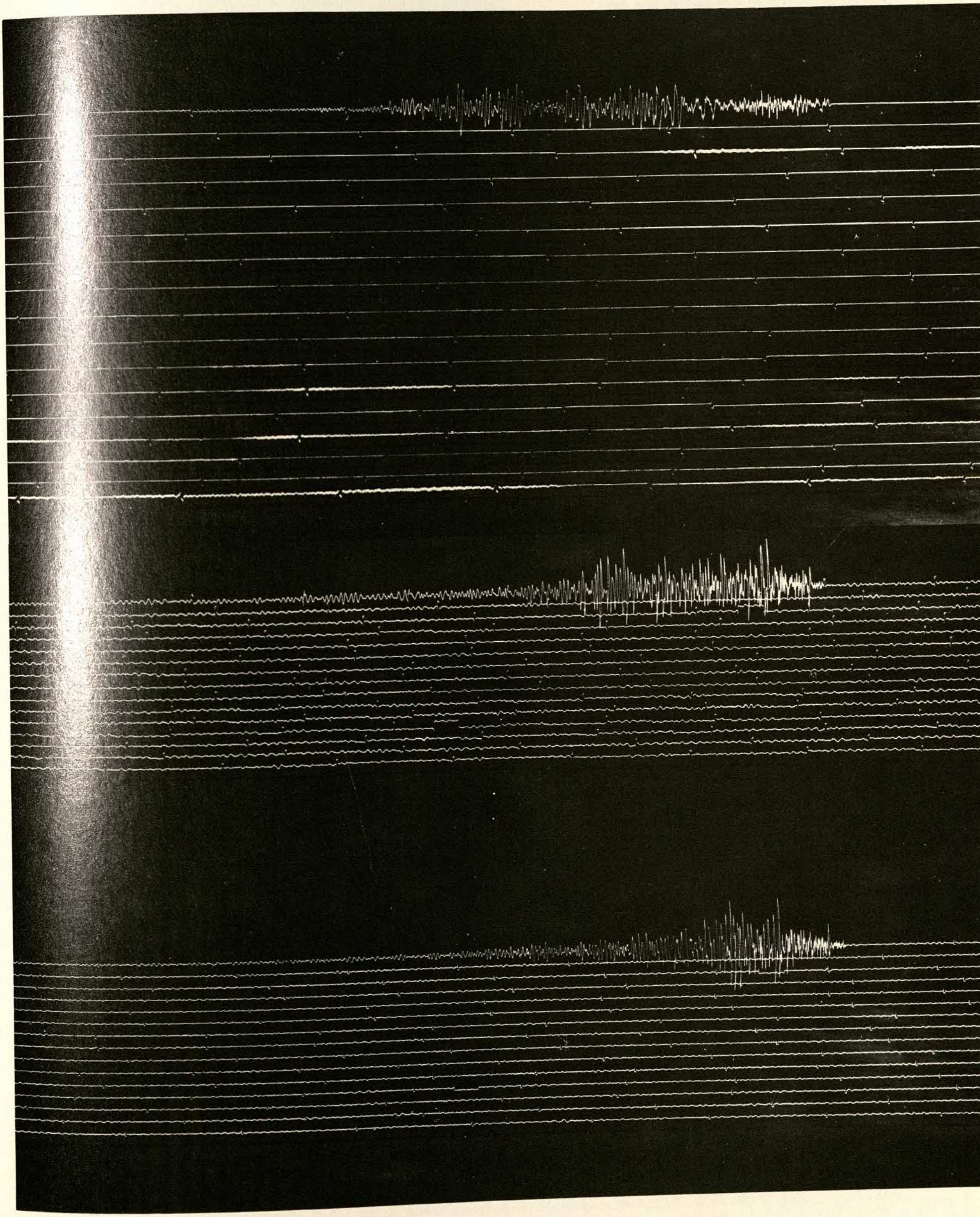
Gusts of the "sirocco" (a hot, dust-laden wind from the Libyan desert that blows primarily in Italy, Malta, and Sicily), are shown in Illustration 4b, blowing east-southeast at speeds of between 57 and 22 kmph. The third seismogram (Illustration 4c) shows gale gusts blowing at speeds of between 22 and 25 kmph.

EARTHQUAKES WITH A DEEP HYPOCENTER—The islands of the Japanese archipelago are subject to a lifting of the land by a process very similar to that of orogenesis. The illustration shows a cross section of Hokkaido island down to a depth of 600 km (about 373 mi). If the scale of depths were to be exaggerated, the mountains on the island and the two ocean troughs between which it is located would become more prominent. The trough on the right reaches its deepest point close to the island; the seabed's rapid descent into the Pacific Ocean marks the edge of the Asiatic continental mass. The depression between the island and the continent of Asia to its left is probably a downward fold in the surface of the continental mass. This hypothesis is supported by the existence of an anomaly in the area's gravity, which indicates the boundaries of the continental mass of sial and its approximate thickness.

Present theories of continental drift and orogenesis indicate that the oceanic floor of basalt is moving laterally toward the continental mass. At the boundaries of the continents, the oceanic floor is bent downward beneath the land mass in the direction of a line joining the dots on the left.

From this basic hypothesis, it is possible to forecast what should happen along the points of this plane of movement. The movement takes place between semirigid rocks, capable not only of transmitting transverse waves, but also of accumulating stresses. Over long periods of time, the rocks are twisted out of shape. Even though the distorting action is a slow process, it may build up stresses capable of causing fractures and, hence, earthquakes. Seismological observatories in the area have precisely located the hypocenters of earthquakes that have taken place, and from this information the accompanying map was drawn.

EARTHQUAKES | methods of location



SEISMOGRAPHIC RECORDING OF AN EARTHQUAKE—The movement of the vertical instrument is indicated by the series of waves at the top; the movement of the horizontal instruments is indicated by the two series of waves at the bottom. The traces are read from left to right (Illustration 1).

According to seismographic records, some 100,000 earthquakes occur each year, or about 300 a day, most of them quite weak and not noticed even by the people living nearby. Earthquakes of minor intensity can be recorded only by instruments within a few hundred miles of the epicenter. Major earthquakes send shock waves to every part of the Earth, and on more than one occasion surface waves have traveled as many as three times around the surface of the globe.

The most intense earthquakes are made up of a long series of shocks. The first of these are usually weak, but they soon become more intense and attain maximum velocity; then they slacken, and the stricken area returns to its normal amount of shock activity. During the earthquake at Tokyo on September 1, 1923, more than 200 shocks were recorded on that day alone, and more than 700 during the entire month; this number fell to 96 in October and 86 in November, then rose again to 139 in December and 167 in January, 1924. In January one extremely intense and destructive tremor occurred—a tremor less severe, however, than that of the previous September 1. Not until about two years later did the number of tremors fall to two a week, the normal number for a highly seismic area such as Japan in general and the Sagami Sea area in particular. It has been calculated that primary waves take about 20 minutes to reach a point on the opposite side of the globe.

SEISMOGRAPHS

Seismologists use special instruments to record movements of the Earth's crust that are of major geological importance. These instruments, called seismographs, are based on certain principles that are worth discussing.

Suppose that a large stone is attached to a long cord, and that the cord is held so that the stone is suspended some distance above the ground. At first, the hand holding the cord is kept still so that the stone does not move; then, the hand is moved very quickly from side to side a few inches; finally, the hand stops moving and returns to its first position. After a short delay (due to the length of the cord), the stone will follow the movement of the hand and will move from side to side. If the stone is suspended by a cord from the ceiling of a room so that the stone almost touches the floor, and the room is moved from side to side by a seismic tremor, the stone will tend to remain motionless for a time while the room moves around it in the course of the Earth's movement. The longer the experiment lasts, the better it works. If a pen is attached to a pendulum at the end of the cord, and a strip of paper is moved along the floor of the room past the pen, the movements of the Earth will be recorded on the strip of paper.

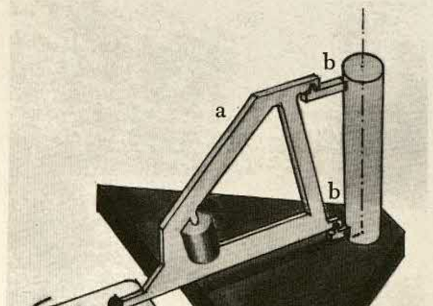
A modern seismograph, however, is not made with a pendulum such as that described to explain the principle of the seismograph. Instead of a heavy weight at the end of a long cord, a device such as that shown in Illustration 2 is used. It consists of a kind of "gate" swinging on two almost frictionless hinges, set almost in vertical alignment. If a weight is placed on this "gate," it will be able to swing laterally on either side of the point of balance, and the more nearly the two hinges are aligned vertically, the further the gate will be able to swing. A device must be provided to record the oscillations and their range, and this usually consists of a pen attached to the "gate"; this pen traces a line on a strip of paper moving beneath it, driven by clockwork, while a special device periodically records the time alongside the line traced by the pen. Thus, if the pen is oscillating during a tremor, a record is made of the precise moment at which the oscillation occurred. This is one of many kinds of instruments devised by seismologists to register and measure the duration of earthquakes. Many seismographs record oscillations photographically.

Considering again the hinged seismograph in the illustration, it is evident that if there are no tremors, the "gate" will hang without moving, pointing in the direction in which the upper hinge is displaced with respect to the lower one. If a seismic movement occurred in that direction, the "gate" would remain motionless. Seismographic stations usually have two of these instruments, one set up along an east-west axis, the other along a north-south axis. If the station should receive waves traveling northeast-southwest, they would affect each of the seismographs with equal intensity; if the waves traveled north-south, they would affect only the east-west seismograph, inasmuch as they would reach the instrument from a lateral direction at an angle to the direction in which the seismograph is pointing. The other instrument would register nothing. Results would be analogous for all the intermediate positions.

The seismographs so far described are useful only to record horizontal movements of the Earth; they are not sensitive to long vertical movements, which are recorded by a different kind of seismograph. This consists (Illustration 3) of a weight hanging from a long spring. A small spring ends in a small tip to which is attached a crossarm that moves like a lever, greatly amplifying any movement of the pendant mass. If the Earth suddenly moved upward, that mass would be pulled upward by the spring; but the stretching of the spring would prevent

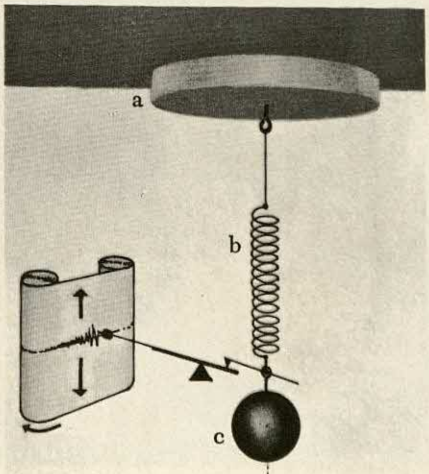
THE HORIZONTAL SEISMOGRAPH—This instrument is composed of a kind of "gate" **a** hung on two hinges **b** with almost no friction and just out of vertical alignment. If a heavy weight is hung on the "gate," it tends through inertia to remain motionless when the ground is shaken by an earthquake. The movements of the earthquake are recorded on paper by a pen inserted into the weighted part.

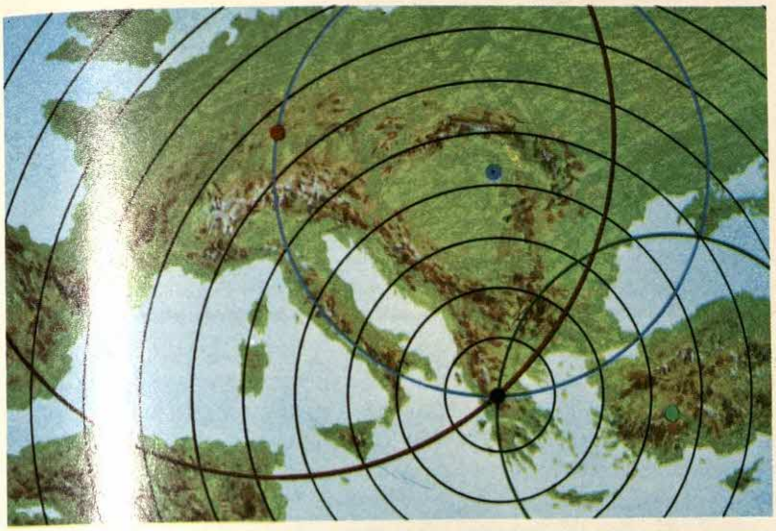
2



THE VERTICAL SEISMOGRAPH—This instrument consists of a support **a** attached to the ceiling, from which hangs a long spring **b** and a heavy weight **c.** Because the vertical movements of the Earth are absorbed by the spring, the weight remains motionless. In this case, too, the Earth's movements are recorded by a pen on a moving strip of paper. The written record is known as a seismogram.

3

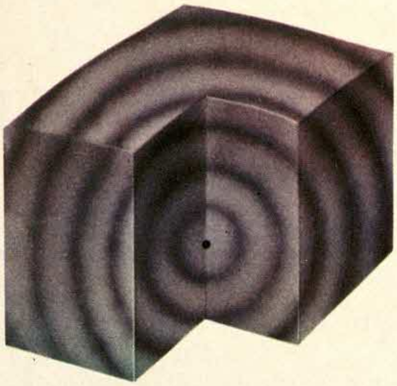




4

LOCATION OF THE EPICENTER—A circle is drawn on a map, with its center (*red dot*) at the first observatory and its radius equal to the known distance of the earthquake from the observatory. The earthquake originated somewhere on the circumference of this circle. Another circle is drawn in the same way centered on another observatory (*green dot*); this circle intersects the first circle at two points. A third circle is drawn centered on a third observatory (*blue dot*); this circle intersects the other two circles at only one point. This point is the epicenter of the earthquake, directly above the point of origination.

5



FOCUS AND EPICENTER—The focus of an earthquake is that point where the earthquake originates below the Earth's surface; it is directly below the epicenter. According to the depth of the focus, earthquakes are shallow (less than 60 km or 40 mi deep), intermediate (from 60 to 300 km—40 to 185 mi—deep), and deep (more than 300 km deep).

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the mass from rising immediately. Before the tension can make the spring raise the weight, the ground level sinks back and the tension is eased. The pendant mass, therefore, tends to remain almost still, while the fulcrum of the rod moves up and down. The opposite end of the rod also moves up and down, and these movements are used to record the vertical movements of the Earth's surface.

THE ANALYSIS OF SEISMOGRAMS

The science of seismology is chiefly concerned with the analysis of seismograms—the records made by seismographs. A few instances will illustrate how the study of earthquakes indicates the internal structure of the Earth.

The task of interpreting earthquakes is far from simple. One reason for this is that each earthquake sends out three main types of waves. Of these, only the surface waves affect all three seismographs (two horizontal and one vertical). In order to interpret a simple seismogram, it will be assumed that the waves recorded on it come from an earthquake that took place at least 620 miles away.

The seismogram in Illustration 1 shows three groups of waves that arrived one after another, the second group arriving 4 minutes 50 seconds after the first, and followed 8 minutes and 20 seconds later by the third. The first group is identified as P waves; the second as S (secondary) waves, which travel more slowly; and the third as the L waves, which travel even more slowly and only along the surface. Tables make it possible to calculate how far away the waves originated. P waves travel at about 8 km (about 5 mi) a second, S waves at slightly more than half that velocity.

The following table shows the various times, in seconds, taken by P and S waves to travel given distances:

Distances	*P waves*	*S waves*
1,000 km (620 mi)	125 sec	225 sec
2,000 km (1,240 mi)	250 sec	450 sec
3,000 km (1,860 mi)	375 sec	675 sec

Now, the S waves arrived 290 seconds later than the P waves; this difference appears in the table to hold for a distance of about 3,000 km (1,860 mi). A table including the travel times of L waves would confirm this calculation. Every seismic observatory has tables for computing the distances of earthquakes according to this method. These tables are the result of long and patient research; each is slightly different because account must be taken of irregularities in the speed of the waves, resulting from differences in the composition of the Earth's crust in the vicinity of each observatory.

When the distance from the observatory is known, the actual location of the earthquake can then be determined. A circle, with the observatory as its center, is drawn on a map; the circle has a radius, according to the scale of the map, of 3,000 km (1,860 mi). Suppose that the earthquake originated somewhere along the circumference of this circle. If another observatory has recorded the same earthquake at 2,500 km (1,550 mi), another circle with a map-scale radius of 2,500 km is drawn centered on that observatory. The two circles will intersect at two points, either of which may be the point of origin of the earthquake. Precise location of the point of origin requires a report from a third observatory, for a third circle similarly drawn intersects the other two circles at one of the two points. Another technique is to use the direction indicated by a pair of horizontal seismographs; this direction, drawn on the map as a straight line beginning at the observatory, would intersect one of the two points on the intersecting circles. In actual practice, computers are also used in locating the earthquake mathematically.

The point so located is called the epicenter of the earthquake, and usually corresponds to the site of maximum damage. This is not, however, the actual point of origin of the earthquake; that point, the focus, usually occurs at some depth below the epicenter. This depth is calculated by rather complex analysis of the waves recorded by seismographs.

THE CLASSIFICATION OF EARTHQUAKES

According to their depth, earthquakes are classified as shallow, intermediate, or deep. Those with a focus less than 60 km (about 40 mi) below the Earth's surface are described as shallow; if the focus is between 60 and 300 km (about 40 to 185 mi), the earthquake is intermediate; if it is below 300 km, the earthquake is deep. The deepest focus recorded so far is 720 km (about 450 mi).

Deep earthquakes generally occur only in Central Asia and in a narrow zone surrounding the Pacific Ocean.

CONTINENTAL DRIFT AND SEA FLOOR SPREADING

confirming a theory

EARLY IDEAS

During the seventeenth century the English philosopher, statesman, and jurist Sir Francis Bacon noticed that the coastlines of the Americas and of Africa seemed to fit together as pieces in a jigsaw puzzle. Since that time scientists have debated the possibility that these continents were once joined together and had only recently been torn apart. This imaginative idea appealed especially to the biologists and paleontologists who had noted the presence of identical fossils in ancient rocks of Antarctica, Australia, South America, and South Africa. It seemed unlikely to these scientists that the evolutionary process could proceed identically in such widely separated areas. It also seemed unlikely that the continents had wandered such great distances. Instead, the paleontologists suggested that land bridges may once have connected many areas of the world. Calling upon mythical land bridges, however, was less than satisfactory.

In the early 1900s the American scientist F. B. Taylor and the Austrian scientist Alfred Wegener independently developed the hypothesis of continental drift. Wegener's book, in particular, became a center of controversy. He suggested that throughout geologic history all of the continents were joined into one "super continent" that he called Pangaea. He further stated that about 200 million years ago, during the Carboniferous period, the continents began to drift toward their present positions.

Wegener supported his theory of continental drift by noting geologic similarities on opposite sides of the Atlantic. One of his chief arguments was based on evidence of glaciation in Carboniferous rocks of South America, South Africa, India, and Australia. Although these continents now lie on either side of the equator, the presence of glaciation in these warm areas strongly supports the idea that they were once grouped together around the South Pole.

Other geologic evidence also challenges the permanency of the continents; for example, ancient mountain systems such as the Appalachians seem to terminate at the Atlantic coastline. Many geologists are convinced that this system is continued in Scotland. In addition to finding evidence of glaciation in present-day equatorial climates, geologists have found deposits of coal and bauxite in northern latitudes, although these deposits are usually associated with tropical climates. Coal beds typical of warm areas have also been found in Antarctica. It seems apparent that either profound climatic changes have taken place or that continents have moved different directions at different times.

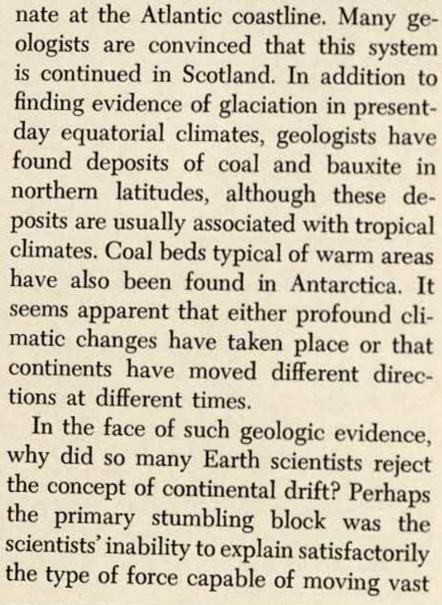
In the face of such geologic evidence, why did so many Earth scientists reject the concept of continental drift? Perhaps the primary stumbling block was the scientists' inability to explain satisfactorily the type of force capable of moving vast landmasses thousands of miles. Wegener suggested that continents could move under the gravitational attraction of the equatorial bulge and under the attraction of tidal forces of the sun and moon. Physicists, however, showed that these forces were too small to move continents.

Other scientists suggested that the position of continents relative to one another has not changed and that changes in climate recorded in the Earth's rocks were due to the entire crust slipping as one complete shell over the underlying mantle (a concept known as polar wandering). Even if adequate forces were found to explain this phenomenon, geologists agree that polar wandering cannot in itself explain the geologic evidence in favor of continental drift.

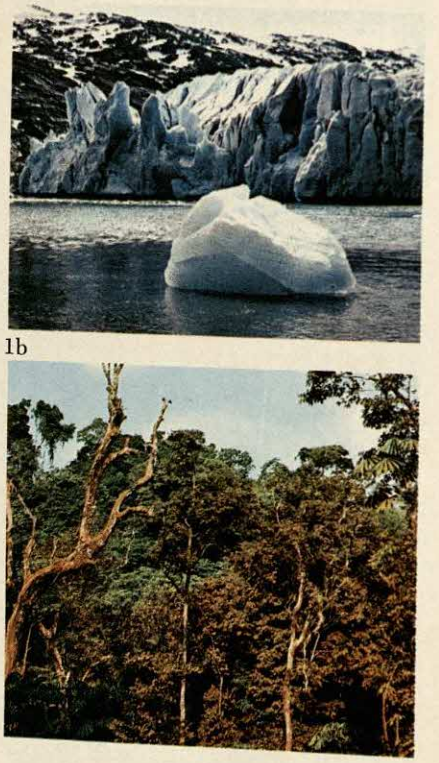
NEW EVIDENCE FOR DRIFT

Until recently many Earth scientists accepted the idea that the positions of the

1a



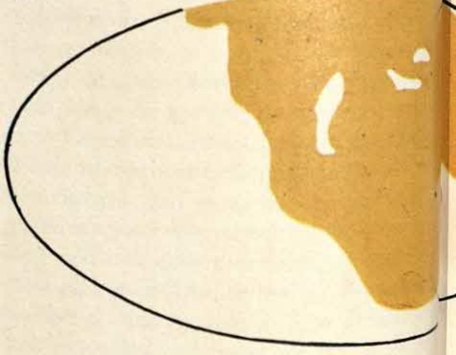
1b



GLACIATION IN EQUATORIAL REGIONS—Lands where warm and moist climates now prevail (Illustration 1b) show evidence of having once been covered by ice and snow (Illustration 1a).

FROM A SINGLE BLOCK TO THE INDIVIDUAL CONTINENTS—The hypothetical continental block named Pangaea split off into fragments during the geological periods. These three illustrations show the reconstruction of the globe according to Wegener, in the Carboniferous period (Illustration 2a), the Eocene (Illustration 2b), and the Pleistocene (Illustration 2c).

2a



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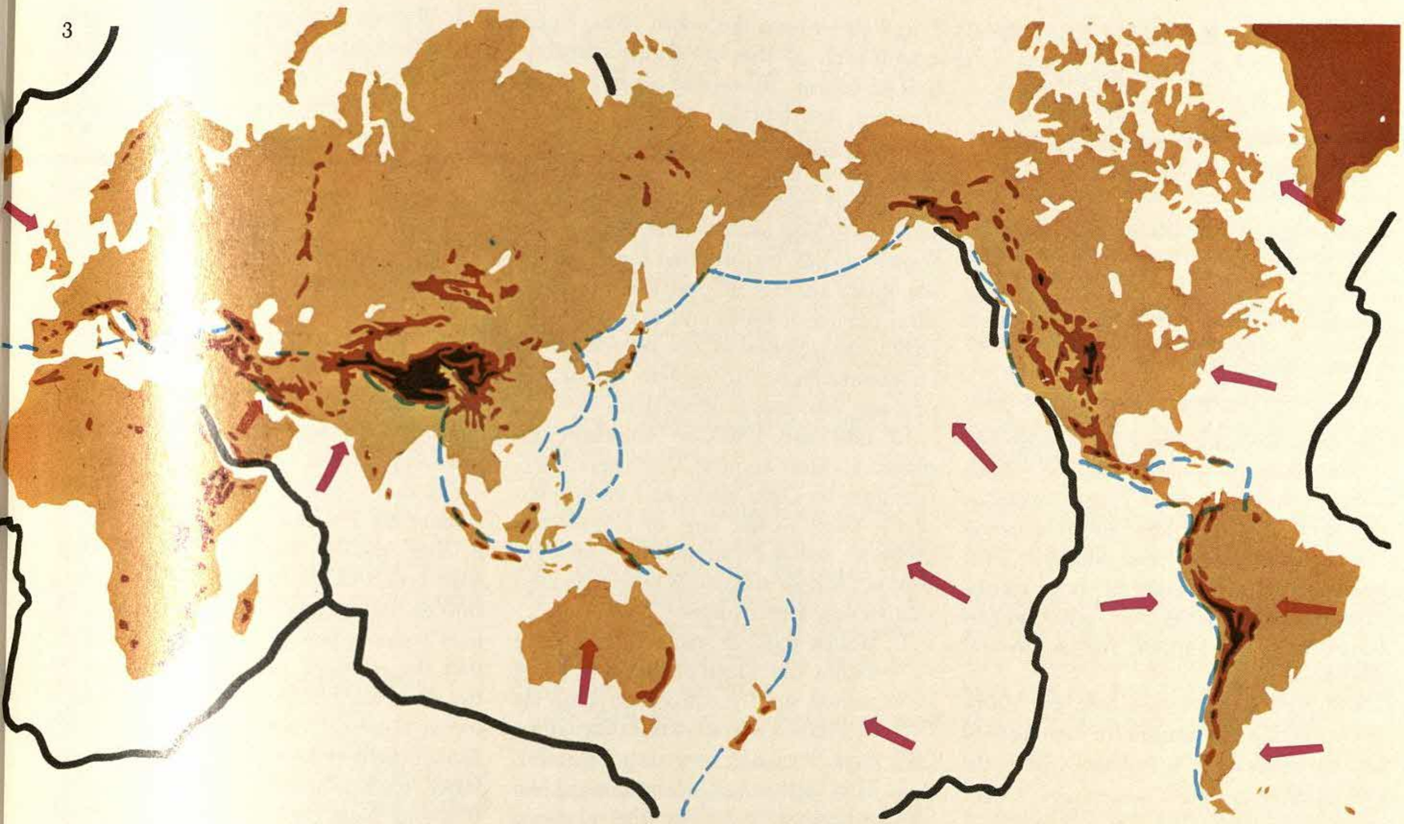


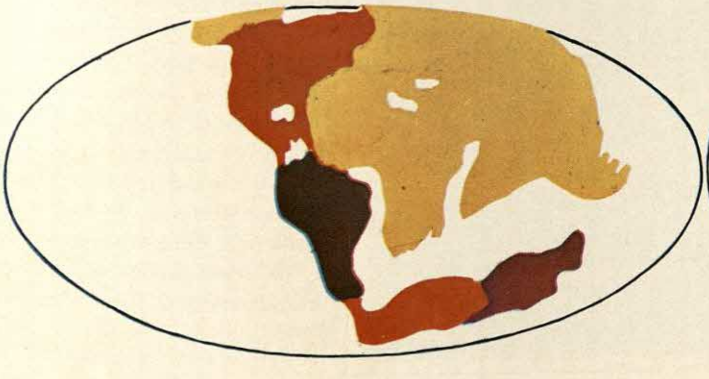
WORLDWIDE DISTRIBUTION OF RIDGES AND ARCS—The entire crust of the Earth may be considered to consist of large plates outlined by oceanic ridges (solid black line) and arc-like belts of volcanism, earthquakes, and young mountains (dashed line). The theory of sea floor spreading suggests that the plates move away from the ridges (in the direction of the arrows) and either bend down into the mantle or buckle in the vicinity of the arcs.

oceans and continents have remained fixed throughout the Earth's history. The continental drift theory was in disrepute until supporting evidence became available from a most unexpected source. In the 1950s, geophysicists such as S. K. Runcorn and P. M. S. Blackett demonstrated that rocks can retain a memory of the position of the Earth's magnetic pole at the time the rock was formed. Rocks being deposited today, for example, would indicate that the magnetic pole is in the vicinity of the geographic North and South Pole. Measurements of ancient magnetic fields (paleomagnetism) revealed a surprising puzzle: the Earth's magnetic pole seems to have wandered about throughout geologic time or, conversely, the pole has remained stationary and the continents have wandered.

Most scientists today believe that the average position of the magnetic pole must be lined up with the geographic pole (or rotation axis), and that the continents themselves have moved. Paleomagnetic studies can reconstruct the latitude of the continents at any specified time in the past and the path they have followed can be charted. The latest paleomagnetic data show that continents drifted in the manner inferred from geologic evidence.

One of the latest techniques to support drift is based on the ability of geochemists to date the age of rocks. Such dating is based on the rate of radioactive decay of certain elements in the rocks.

2b



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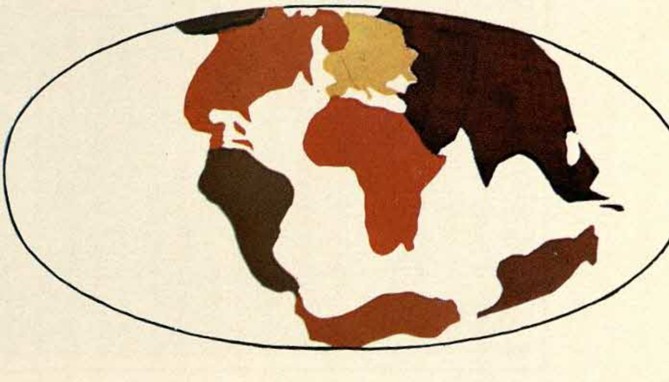
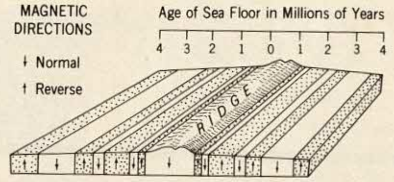




MAGNETISM OF THE SEA FLOOR—Rocks on the ocean floor display a pattern of magnetization that is symmetrical about a central oceanic ridge. Such a pattern would result from periodic reversals of the Earth's polarization if the rocks were moving laterally away from the ridge in both directions.

The American physicist P. M. Hurley has shown that the position of the oldest rocks in South America exactly matches the position of the oldest rocks in Africa —as if the two were once adjacent. So it appears that age dating of rocks constitutes the latest and perhaps most powerful technique to support the continental drift hypothesis.

Despite vigorous research by Earth scientists, the mechanism for moving continents remained a mystery until the early 1960s.

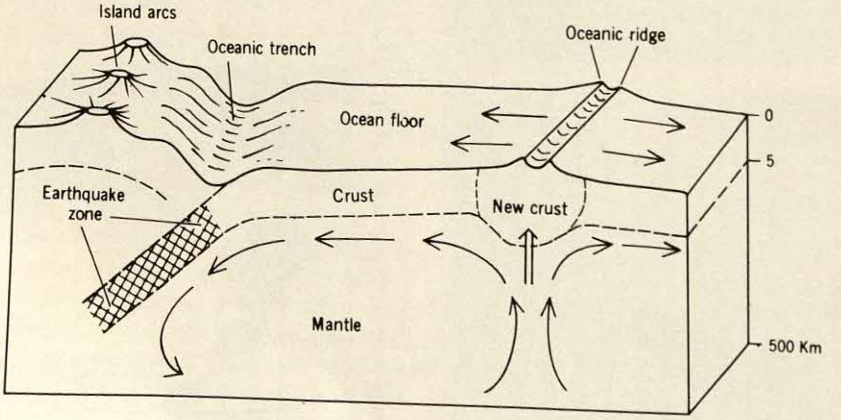
SEA FLOOR SPREADING

The key to how and why continents are able to move turns out to have been hidden beneath the oceans. Oceanographers only recently have demonstrated that the sea bottom hides a continuous chain of mountains about 64,000 km (about 40,000 mi) long, several hundred kilometers wide, and about 3 to 8 km (about 2 to 5 mi) above the ocean floor. Upon examination of the worldwide distribution of oceanic mountains, deep oceanic trenches, earthquake zones, and volcanoes, a startling fact becomes evident: these active features are not randomly distributed, but seem to be carefully lined up in long narrow belts, often in the form of an arc. It seems that forces within the Earth are still shaping these tremendous arc-like features and that whatever hypothesis applies to the movement of continents must also explain the nature of these worldwide active belts.

In 1961 and 1962 the American geologist H. Hess and the American oceanographer R. Dietz integrated knowledge of the Earth's crust into an elegant hypothesis: sea floor spreading. The concept is a simple one that is best explained in a step-by-step manner.

1. Molten rock, or magma, from deep within the Earth's mantle is being carried up by convection currents and forced into a central ridge along most oceanic mountain systems. This activity is characterized by volcanism, including the presence of high heat flow and minor earthquakes along the ridge.
2. As the magma moves upward into the central ridge, it solidifies and forms a new sea floor. The old sea floor is forced laterally away from the ridge, either under the wedging action of the new material, or carried, conveyor-belt-fashion, by the convection currents in the mantle.

SEA FLOOR SPREADING—One of the newest hypotheses suggests that magma is brought up beneath the central ridge and solidifies as new ocean floor. The old sea floor spreads away from the ridge, eventually being swept back into the mantle.



3. The sea floor spreads outward from the central ridge, pushing continents before it. Eventually, the moving crust is bent downward into ocean trenches and absorbed back into the mantle, usually in the vicinity of arc-like volcanically active belts, such as the Andes or the arc formed by Sumatra, Java, and the Lesser Sunda Islands.

TESTING THE THEORY

Earth scientists are now testing and modifying the basic concept of sea floor spreading. Perhaps the strongest supporting evidence thus far comes from paleomagnetism. Following the suggestions of F. Vine and D. Mathews, geophysicists have noted that oceanic rocks on either side of the central ridge are magnetized in a symmetrical pattern. They suggest that the new sea floor is magnetized in the direction of the magnetic field existing at the time they are deposited. The Earth's field is known to change its polarity frequently, and the record of positive and negative magnetism is carried laterally away from the central ridge in both directions as a symmetrical magnetic pattern.

Some scientists now assert that Africa and Arabia represent an active example of two continents beginning to drift apart. The Red Sea and the Gulf of Aden thus represent a new ocean floor less than 20 million years old (quite recent in terms of geologic time). A central ridge extends from the Indian Ocean into the Gulf of Aden. The telltale symmetrical magnetic pattern is also present.

From where and when will the next important evidence come? Surprisingly enough, the answer may come from the moon. Observation stations in Hawaii and Japan are now being planned—stations from which an intense pulse of laser light will be sent. The beam will bounce off a reflector placed on the moon by the astronauts of Apollo 11. If continental drift is a reality, then Hawaii should be moving toward Japan at a rate of about 4 inches per year. If such a variation in position is detectable over a few years by the laser experiment, the continental drift theory will have been further confirmed.

(A. J. R.)

THE EMERGING EARTH

the origins of plains and mountains

The Earth's landscape is a fascinating spectacle, composed of such diverse elements as magnificent mountains and broad, sweeping plains. The study of how it came to be that way is equally fascinating. Constant internal movements of the Earth led the fluid magma from its interior up toward the crust and sometimes to the surface. Certain phenomena modified the surface of the crust, making it appear as it does today.

To understand the development of life on the Earth, it is necessary first to understand what happened to the terrain on which this life was born and nurtured. The study of the structure of Earth's crust is an essential key to this understanding.

SHIELDS AND CONTINENTAL PLATFORMS

The regions most deeply involved in the geological phenomena that have marked the Earth's history are the upper parts of the continental masses. Foremost among these regions are the "great plains"—those vast, extended plains that cover a large part of a continent, such as the northeast Canadian plain and those in Sweden, Finland, and most of the Soviet Union. Other great plains (or high plains) are found in Africa, Australia, and India. These continental structures are extremely old, certainly many hundreds of millions of years, and are referred to as cratons. The great plains have different origins and are of two physically different types: shields and platforms.

Shields are those parts of the Earth's crust, generally rather flat, that have not undergone wrinkling since Precambrian time and, in general, have not been covered with sediment. These include the Finno-Scandinavian shield, the Canadian shield, and others. The Finnish landscape, for example, is made up of a large mass of granitic rocks only partially covered by a layer of soil. By comparison, in Italy such naked rock is seen only on the eroded sides of the highest mountains.

Platforms, or table regions, are, like the shields, vast masses of igneous or metamorphic rocks smoothed by erosion and subsequently covered with a layer of sedimentary rocks. Early in their history, these rocks were forced by gigantic pressures to fold into mountain chains. The wind and the sea then gnawed away at these mountains, reducing them in the course of millions of years to slight undulations in an immense flat area. When the sea flooded the plain, it deposited sediments on it. For all this to take place, tens and maybe hundreds of millions of years had to pass.

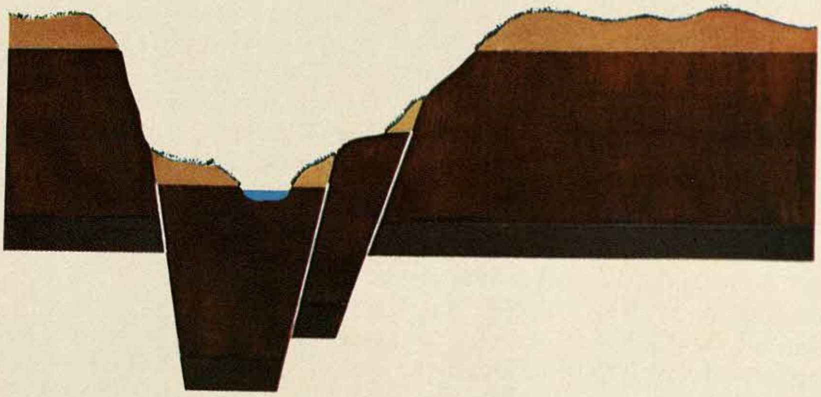
Finally, the sediments were raised slightly out of the water and solidified to form the rocks that are now a sedimentary blanket over the magmatic mass lying underneath. When they rose, the layers of covering matter remained almost horizontal and flat; thus, the terms platform and table region.

The thickness of the blanket of rock may be as great as a few kilometers, or it may be much less. Atmospheric agents continue their inevitable work of erosion; but where the rocks have not risen too high and the plain is only slightly above sea level, the erosion is not very extensive. This is the situation in the table region of European Russia and Siberia. However, many of the table regions of Africa, which were pushed up to much greater heights, have been deeply eroded and furrowed by rivers.

FAULT ZONES, GRABENS, AND HORSTS

When distortions are produced by forces acting on the continental masses, the results may appear in different ways. They may give rise to folds and fractures, but these are not always concomitant.

STROMBOLI—The typical shape of volcanic mountains is conical with a somewhat flattened top—a characteristic especially evident in volcanoes of recent origin such as Stromboli.



A TECTONIC TROUGH—The distortion of continental masses may produce almost vertical fractures. The outward movement of masses of rock creates zones of depression called grabens or tectonic troughs. The Rhine River runs through a graben.

Often, vast areas of the continental masses are furrowed by enormous fractures that divide them into fragments, some of which sink and some rise. The fractures in the rock layers and masses are called faults; the areas in which they occur are called fault zones. The fractures characteristic of such areas are mostly vertical, or at a slight angle to the vertical.

If a continental mass is fractured by forces pulling two of its sides in opposite directions, as in Illustration 2, some fragments of the mass are likely to sink. The depression is called a graben or tectonic trough. If the fractures are created by pressure rather than by traction, however, the blocks in the center of the compressed area will rise rather than sink, creating pillar-shaped bodies called horsts. These raised blocks maintain the shape they had when they were part of the mass—the lifting causes no distortion or wrinkling.

A fine example of these formations can be seen in Europe. The Rhine River runs through a giant graben, of which it occupies only a part. Flanking it are two huge horsts—the raised regions of the Vosges in France and Germany's Black Forest. Other great systems of such faults are found in east Africa.

RECENT MOUNTAIN FOLDS

The large mountain chains that border or cut across the continents are all examples of recent folds. These include the Alps, Apennines, Carpathians, chains in the peninsula of Asia Minor and in Iran, the Himalayas, the partially submerged chains of southeast Asia and in the Sunda Islands, New Guinea, and New Zealand, as well as the Rocky Mountains and the Andes.

These mountains were all products of the orogenic process. A great difference exists between such mountain chains and ground that has been pushed up into platforms or horsts. The structure of these folds is fairly complex. Not only have they given rise to undulations of the ground and rocks, through which rivers have then begun to flow, but in some instances they have also formed folds so greatly accentuated that they bend over sideways to cover the surrounding ground.

Geologically speaking, these phenomena have occurred in a short period of time compared with the time required for the formation and development of a shield or platform. Furthermore, during the formation of the mountains, water immediately began eroding them, following the lines that the shape of the fold had formed into valleys. Like the waves of the sea, these undulations were parallel, so that the valleys have generally cut up the mountainous areas into groups parallel to one another and perpendicular to the direction of the thrust that generated the folds. For this reason, mountain systems that are orogenically young typically have valleys parallel to each other.

On the other hand, valleys furrowing table regions, high plains, or pillars may run in any direction. This characteristic arrangement of valleys gives the Earth's surface two clearly different patterns, which can be readily distinguished on a map with contour lines or colors to indicate different heights above sea level.

VOLCANIC MOUNTAINS AND TABULAR EFFUSIONS

Volcanoes and tabular effusions often constitute important elements in the structure of the upper part of the Earth's crust. Volcanoes are formed when gases, fluids, and solid matter produced by underlying magma are forced to the surface. The activity of a volcano lasts for only a limited period—the volcano remains active as long as the magma feeding it remains hot. Only rarely is the lifespan of a volcano more than 10 million years. For a period of time after it stops erupting, a volcano manifests secondary activities, such as the production of thermal springs, vapors, and ground heat. When this activity also comes to an end, the volcano's life is over.

Many active volcanoes are known. Among the most famous are Vesuvius, Etna, Stromboli, Kilimanjaro, Fujiyama, and those of the Hawaiian Islands, Java, and Iceland. The Bohemian Mittelgebirge is an example of a very ancient volcano. Still more ancient are the volcanoes in South Africa, of which nothing now remains. Their lava flows have been mined to extract diamonds from the solidified rocks of which they now consist.

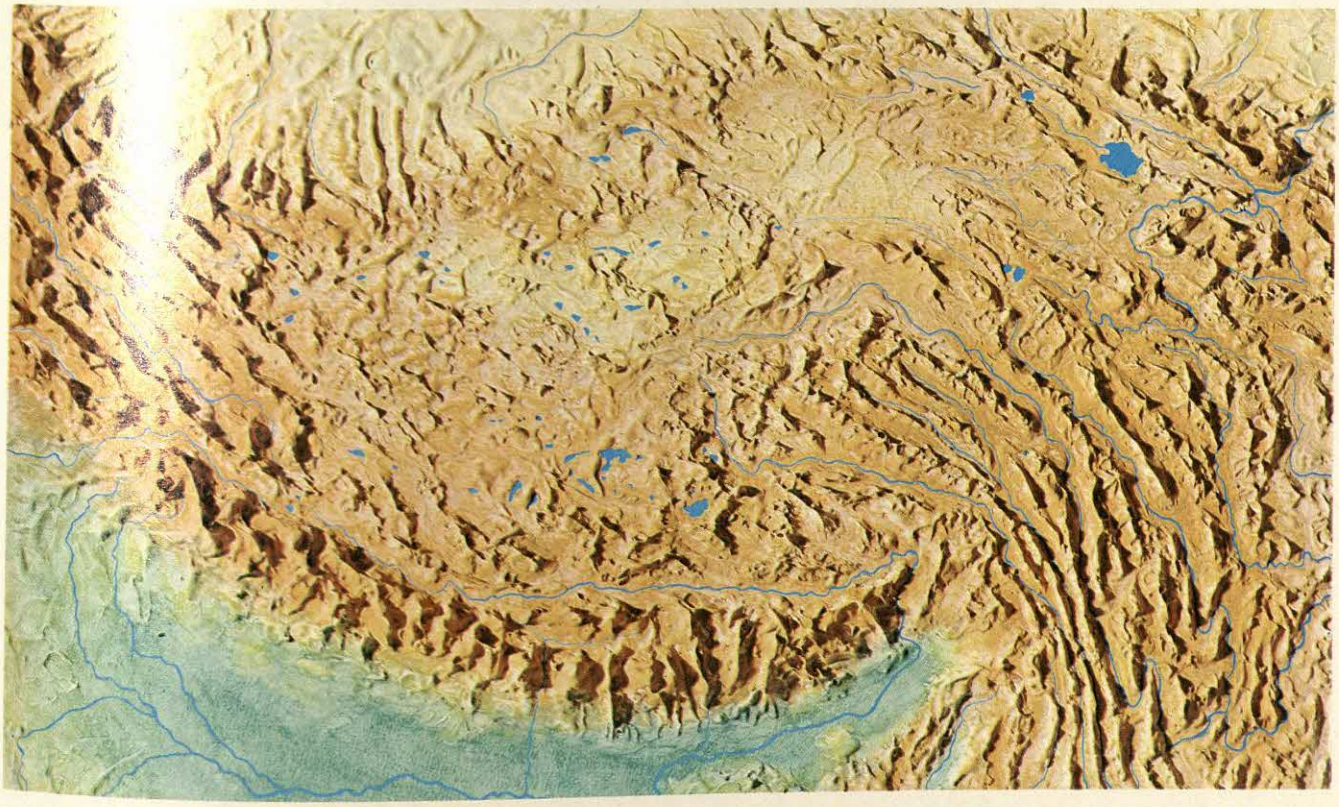
Volcanic peaks are never very high. Only the large African volcanoes are higher than the highest European peaks. Nevertheless, volcanoes that have created the most colossal eruptions ever known (such as those that gave birth to the Hawaiian Islands) rise higher above the ocean bed than Everest rises above the plains surrounding the Himalayas.

The volcano, a mountain built up by eruptions, is only one of the forms that may be taken by lava disgorged from the ground. Sometimes, numerous outlets are grouped in a limited area or arranged in a line. When the liquid lava erupts, its effusion may cover vast areas with a fairly thick layer of matter. An example of this kind of tabular effusion is found near Bolzano, Italy. The valleys cutting through the porphyries are etched into an ancient tabular effusion that stretches for hundreds of square kilometers.

The active and recently active volcanoes are concentrated in a great belt encircling the Pacific Ocean and in a shorter belt from the Solomon Islands through New Guinea and Indonesia.

Although the continental United States is commonly thought to be free from volcanic activity, the Cascade Range in the northwestern part of the country is part of the circumpacific belt; it contains many recently extinct volcanoes and several that should be considered active. The eruption that produced Crater Lake occurred only about 6,000 years ago. About a dozen eruptions have taken place in the Cascade Range since early in the nineteenth century. The most recent of them, at Lassen Peak, California, during the years 1914 and 1917, produced violent explosions, glowing avalanches, mud flows, and a small lava flow.

THE HIMALAYAS—This mountain chain is an example of recent folding. The folds and coverings are represented by a succession of parallel chains separated by longitudinal valleys. When the mountains were forming, water began to erode them, following the folds.



SUBMERSED LANDS

Vast areas of the Earth's surface are covered by the seas. Yet in most coastal areas, no clear geological distinction exists between the land above the water and that beneath it. Rather, there is an extended transition zone known as the continental shelf.

The continental shelf generally follows the coastal outline, gradually sloping into the sea to an average depth of 135 m (about 440 ft), but seldom to a depth of more than 200 m (about 650 ft). The shelf may extend a considerable distance —as much as 500 m (about 1,600 ft)—before the seabed falls sharply into the depths of the ocean floor. This is because of the structure of the continental mass; the shelf and the visible part of the continent form a single body of sial overlying the sima. The sima is a shell of basic rock composing the lower part of the Earth's crust.

The shelf or platform is actually visible, from high altitudes, as a border around the continents. In some regions, however, the shelf is almost or even totally nonexistent. One such region is along the Pacific coast of South America. In other regions, the shelf may extend a great distance—as, for example, around the British Isles, where it actually forms a submerged bridge between Greenland and Europe.

The seas were not always at their present levels. In some past epochs, they were higher; in others, lower. These variations were primarily caused by the Ice Ages. The accumulation of ice in thick and extended fields removed water from the sea, and the sea level consequently fell, revealing part of the continental shelf. The Antarctic ice cap is an example of this; if it were to melt now, the sea level would rise by at least 50 m (about 160 ft).

During the last Ice Age, the presence of ice over a large part of Scandinavia and the Alps must have greatly lowered the sea level and revealed much of the continental shelf, giving the continents a much greater land expanse and a considerably different coastline from that of today. Whole seas were dry land, islands were peninsulas, and archipelagoes were parts of continents. For example, the Adriatic Sea did not exist—land was there instead. (Today, the bed of the Adriatic is still furrowed with the courses of once-great rivers that now make only the very short journey from the peaks of Italy's Apennines to the nearby sea.) England was a peninsula stretching northward from the European continent, while the Malaysian archipelago was a land bridge between Asia and Australia.

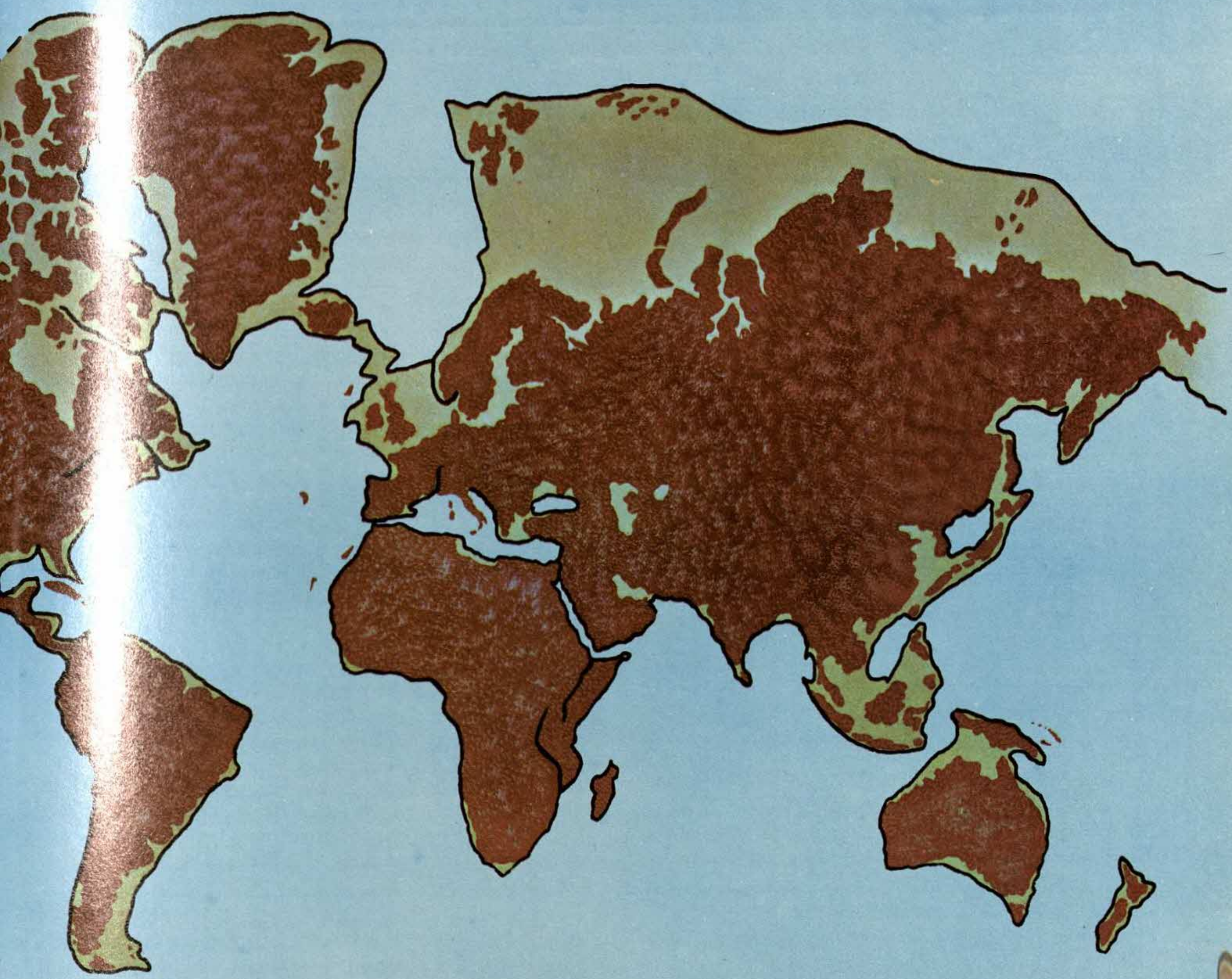
During this same period, other geological areas were submerged beneath the sea. Today, many of these areas are parts of the great landmasses of the continents.

The existence of the continental shelf is of great importance to the geological history of the Earth's crust. The sea that washes over the shelf is called the epicontinental sea; it covers an area that is extremely rich in flora and fauna. Because this part of the sea is relatively shallow, most of the sun's light passes through it, providing seabed conditions favorable for an active growth of marine vegetation. This in turn forms an ideal environment for the development of a fauna that is rich in both number and variety. The currents that sweep the epicontinental sea carry river sediments across its entire expanse; these too contribute to the activity of the seabed through the sedimentation of organic waste.

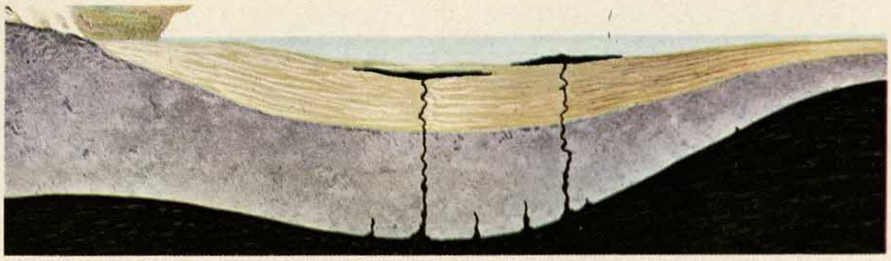
With the recognition that the continental shelves are structurally part of the continent and contain mineral deposits similar to those of the adjacent land, their economic importance increased.

GEOSYNCLINES

Sometimes, two continents are separated by a depression of the lithosphere (the solid part of the Earth) below the surface of the water. The continental limits are defined by a sea that is totally, or almost totally, surrounded by land. Sediment from the surrounding areas is deposited in these depressions, which are called geosynclines. One example of such a geo-



THE SHELF SURROUNDING THE CONTINENTS—The green area marks the extent of the continental shelf; the black line is its limit. The darker areas are the continents.



A GEOSYNCLINE—The accumulation of sediment in a shallow sea causes a further sinking of the seabed according to the laws of equal contours. This curving of the Earth's sialic crust forms a depression that is known as a geosyncline.

syncline is the Mediterranean Sea.

During the Mesozoic period, a colossal geosyncline called the Sea of Thetis (Thetis was the sea goddess of Greek mythology) extended from the present Mediterranean Sea to the Sunda Sea in the Malaysian archipelago, separating Europe and Asia to the north from Africa, Arabia, and India to the south. From this geosyncline arose the chains of the Alpine-Himalayan mountain system. The present Mediterranean is what remains of this ancient geosyncline.

Geosynclines totally surrounded by land are destined to fill up rapidly with sediment, which may rise above the water level to a height of several kilometers.

THE OCEAN BEDS

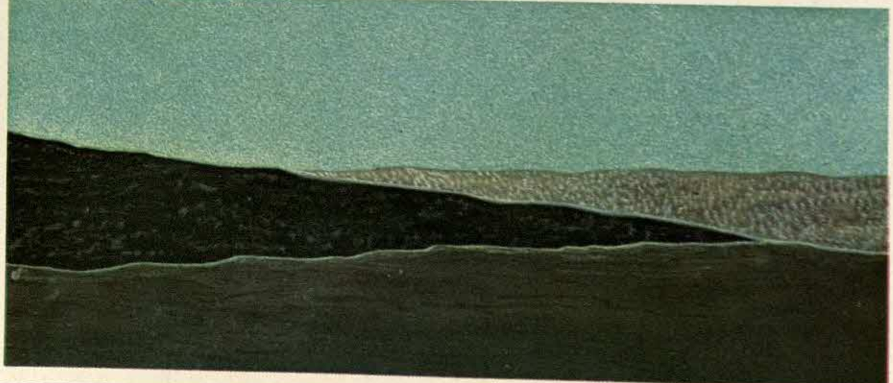
The ocean beds beneath the vast areas of water separating the continents are generally more even than the continental masses, with relatively few mountains and troughs. They are covered with abyssal sediment, under which stretches a fine layer of sima. It is believed that in some large areas such as the central zone of the Pacific basin, the sima is overlaid by only minimal deposits of abyssal sediment.

Far from the continental coastlines, large islands, mostly of volcanic origin, rise from the ocean beds. These islands are often grouped in archipelagoes, arranged in lines that may extend for hundreds of kilometers. Some of the volcanoes are still active; others are completely inactive. On many of them, coral grows, and as the inorganic material accumulates, the dimensions of the island grow rapidly.

Over a large part of many ocean beds (for example, those of the Pacific) lava banks have been formed by submarine eruptions. Because of the great depths of the ocean, the molten lava is rarely visible on the surface, and the many thousands of meters of water are opaque to the most intense light. The extremely great pressure of the water even prevents the lava from releasing vapors or fumes. Only a boat directly over a submarine eruption will react to such a cataclysm; the boat will vibrate as though scraping an invisible reef. This is caused by the sound waves produced by the subterranean explosions and transmitted through the water.

Because the erosive forces that tend to obliterate continental features are lacking in the ocean, volcanic peaks are relatively more prominent and persistent in the ocean than on land. In 1837 the British naturalist Charles Darwin suggested that coral atolls form on top of volcanic peaks that have reached the surface, the upward growth of coral proceeding at a rate that balances the downward sinking of the peak through isostatic adjustment. The drillings and other geophysical measurements that have been made on atolls confirm this theory. Additional confirmation was provided in 1946 when it was learned that hundreds of flat-topped seamounts (volcanic peaks that do not reach the surface) are scattered over the Pacific. These "tablemounts" apparently are ancient volcanoes, the tops of which were eroded by wave action at sea level and which later were submerged to depths of 3,000 to 6,000 ft—too rapidly for coral accumulations to maintain them as atolls.

THE OCEAN DEPTHS—The illustration shows a seabed at a depth of about 3,000 m (about 10,000 ft). Under the water are layers of liquid sediment, injections of sima, and solidified sediment. Much can be learned from the ocean depths about Earth's climate in past ages.



CONCORDANT INTRUSIONS

intrusions following lines of least resistance

The rocks of the Earth's crust and mantle are mostly solid. At a depth of 100 km (about 62 mi), the temperature is probably close to 1,000° C (1,832° F); only the high pressure there keeps the rocks at this depth from passing into the liquid state. Certain regions between the sial and the sima have locally high temperatures, and the rocks there are in the molten form known as magma. The magma, having a rather plastic consistency, is able to move or flow, sometimes approaching the surface of the Earth, and occasionally erupting onto that surface.

A small variation in the temperature of the magma is enough to effect the release of gaseous substances. The pressure exerted by these gases pushes the magma in many directions, but particularly upward, and enables the molten material to open a passage among the most compact rocks by splitting them or melting them. The magma, after intruding the cold rocks of the crust, stays hot for a relatively long period of time. The temperature then drops slowly as the heat is dispersed and the mass of intruded magma solidifies.

PLUTONS

A mass of magma that has solidified within the Earth's crust is called a pluton. Some plutons, of limited extent, were formed when a certain quantity of magma was injected into the overlying rocks from below. These particular plutons, whose lower limits are known, are called injected or intruded bodies.

Another type of pluton is called a batholith. So far, scientists have not been able to establish the lower limits of a batholith; therefore, it is believed that a batholith is rooted in the sima. Batholiths often have vast dimensions. The largest of the known batholiths forms a large part of the northern region of the Rocky Mountains. It measures about 2,000 km (about 1,200 mi) in length and about 200 km (about 120 mi) in width.

The intrusion of magma into rocks is a difficult process. If the magma opens up a path for itself by following the lines of least resistance—for example, along planes of stratification, along planes of schistosity, or even half-opened fissures—the plutonic rock is said to have been produced by concordant intrusion. If the magma cuts across bending or foliation by following the paths of greater resistance, the plutonic rocks are said to result from discordant intrusion.

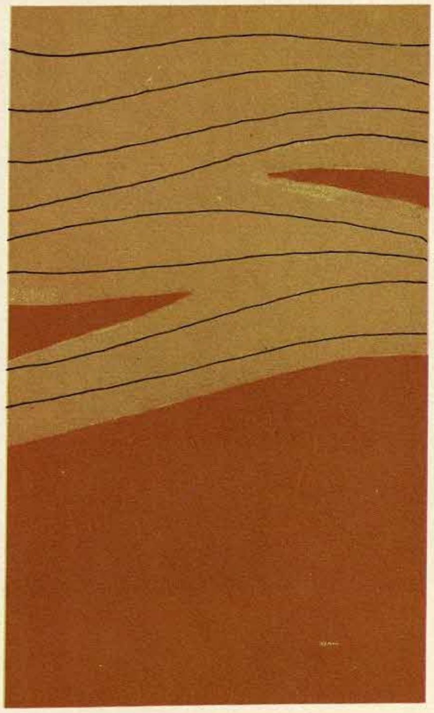
The underground movements of magma must have been extensive for plutons to take on the innumerable forms observed by geologists. Magma rarely appears on the surface of the Earth as a result of volcanic phenomena, and plutons are observed only when erosion has brought them into the light of day. Consequently, difficulties may arise in identifying the origins of igneous rocks. These origins may be determined only through a precise examination of the relationship between the intrusion of magma and the surrounding rocks.

SILLS

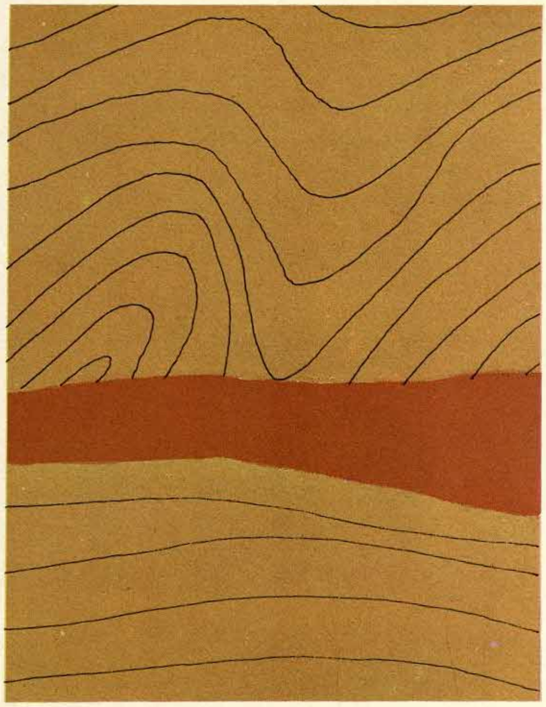
Sills are intrusions of extremely fluid magma between the rock's planes. Intrusions of this type are found in many geological situations—for example, in tabular platforms made up of sedimentary rocks; here magma opens, with relative ease, a path between the planes separating the various sedimentary strata. Crystalline rocks, which are formed by the solidification of magma, also often break along certain lines with great ease. Sills are found whenever the magma is fluid and under high pressure. Intrusions of varying thickness have been produced through this mechanism; the thickness may vary from a few millimeters to hundreds of meters. The horizontal extension of a sill may cover an area measuring thousands of square kilometers.

How is the magma able to penetrate into the rocks and make room for itself?

AN EXAMPLE OF CONCORDANT INTRUSION—This illustration shows clearly that the magmatic injection and the rocks surrounding it lie in parallel layers. The magma enters the rock, following the lines of least resistance offered by the rock, such as planes of schistosity, stratification, or fracture.



INTERFORMATIONAL SLAB—When a sizable quantity of magma is injected between two rocky formations of different ages and configurations, the intruded material forms an interformational slab. It follows the boundary between rocky formations in which distorted layers are superimposed on parallel layers.



It is clear that the magma must be under very high pressure to be able to lift the overlying rock layers, heavy as they are. For example, a sill in the process of formation a thousand meters below the surface must have a pressure of at least 300 kg/cm^2 (about 4,300 lb/in.^{2}) to lift up the overlying rock strata.

Sometimes, the intrusion of a sill takes place because the underlying strata are pushed downward, even though the position of the higher rock strata stays as it is.

In some cases, sills are formed along the surface separating two rocks of completely different nature and origin; such sills are called interformational sills.

Erosion may uncover a sill by removing the soft rocks lying on top of it. The sill then forms a tabular region whose size depends on the extent of the erosion that has uncovered it. Sills that have been formed from extremely liquid magma often produce basaltic rocks when they solidify. When they fracture, basaltic rocks may produce hexagonal prisms that are often arranged vertically.

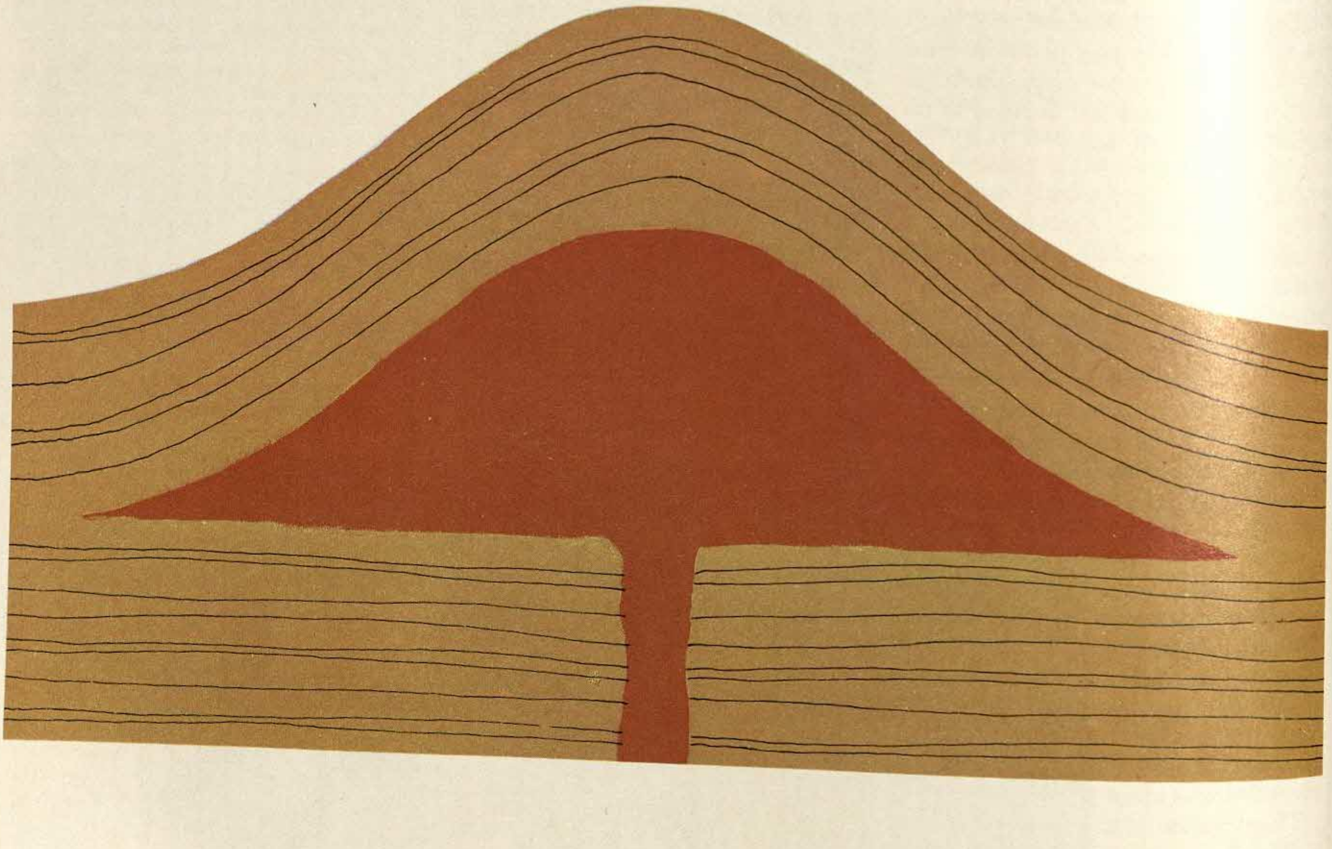
INTERFORMATIONAL SLABS

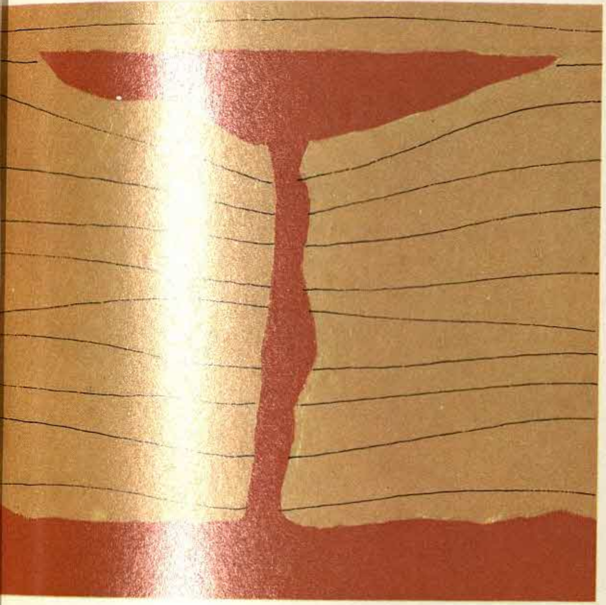
An intrusive body similar to a sill, but thicker and stumpier, is called an interformational slab. It follows the boundary between two rocky formations in which greatly distorted layers are superimposed on parallel layers; that is, the interformational slab is deposited on the edge of a stratigraphic discordance. When the magma reaches the stratigraphic discordance, after rising through the rocks, it is easily injected along the plane separating the two formations, thereby producing the slab.

LACCOLITHS

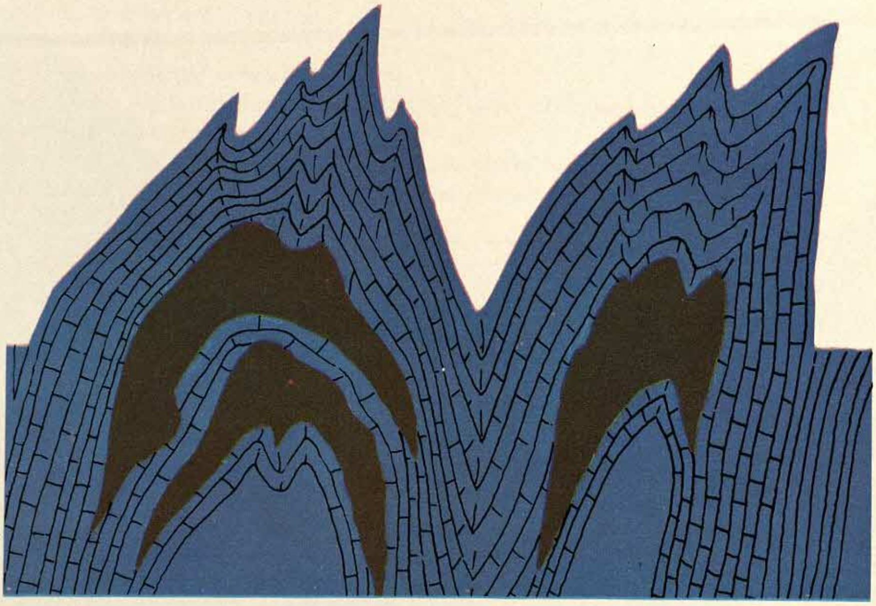
Sometimes, the magma intruding into the strata of a tabular region exerts sufficient force to lift up the roof of the space it occupies. In other words, it is easier for the magma to lift and inflate the strata overhead than it is to intrude between them over a vast area. As previously noted, extremely fluid magma gives rise to sills. Denser magma, on the other

LACCOLITH—This formation occurs when a dense magma rises from the depths of the Earth through a channel and expands horizontally, lifting the overlying rock strata and imparting to them a domelike appearance. The low temperature of the magma does not, however, generate eruptions. Because laccoliths often form in groups, they give a characteristic appearance to the landscape.





LOPOLITH—The pluton known as a lopolith has a shape opposite that of the laccolith. Instead of lifting the overlying strata, the magma pushes down underlying strata.



PHACOLITH—In this formation, magma injected into the highest region of a large fold occupies cavities between the various strata. The rocks on the flanks of the fold are extensively compressed. In a vertical section, the phacolith looks like a meniscus.

hand, when injected under similar conditions, gives rise to laccoliths.

For a laccolith to form, the magma must be dense and the depth at which it starts to expand horizontally must not be too great. The ballooning of the upper strata of the ground as a laccolith intrudes into them sometimes fractures these strata and leads to the formation of a flower-shaped head of magma. The low temperature of the latter indicates that it does not give rise to eruptions. Uneroded laccoliths are characterized by the strange way in which they cause the Earth's surface to balloon upward; moreover, because laccoliths often form in groups, they give the landscape a characteristic appearance.

The name *laccolith* was first used to describe the Henry Mountains of southern Utah. Their characteristic is that they have spread out along the bedding planes of the strata but are not so broad and thin as the intrusive sills that, consisting usually of basic rocks, have spread over immense distances without attaining much thickness. Typical laccoliths have a domed upper surface and a flat base. In the Henry Mountains, the formations are from one to five miles in diameter and range up to 5,000 ft in thickness. In western South America, similar laccoliths occur.

The kind of injection that leads to laccolith formation sometimes takes place in a rather strange way. The magma rises from an underlying basin through a conduit that emerges between two strata. As the magma rises, it fills the space between the two strata, but empties the basin below; the roof of the basin then sinks. The intruded mass that is formed has a flat roof and a convex lower surface or "bed." A pluton of this kind is called a lopolith.

PHACOLITHS

The hinges of the great folds in the Earth's crust are often fractured and full of cavities. Magma is sometimes injected concordantly into the crests and troughs of these folds. Plutons formed in this way are called phacoliths.

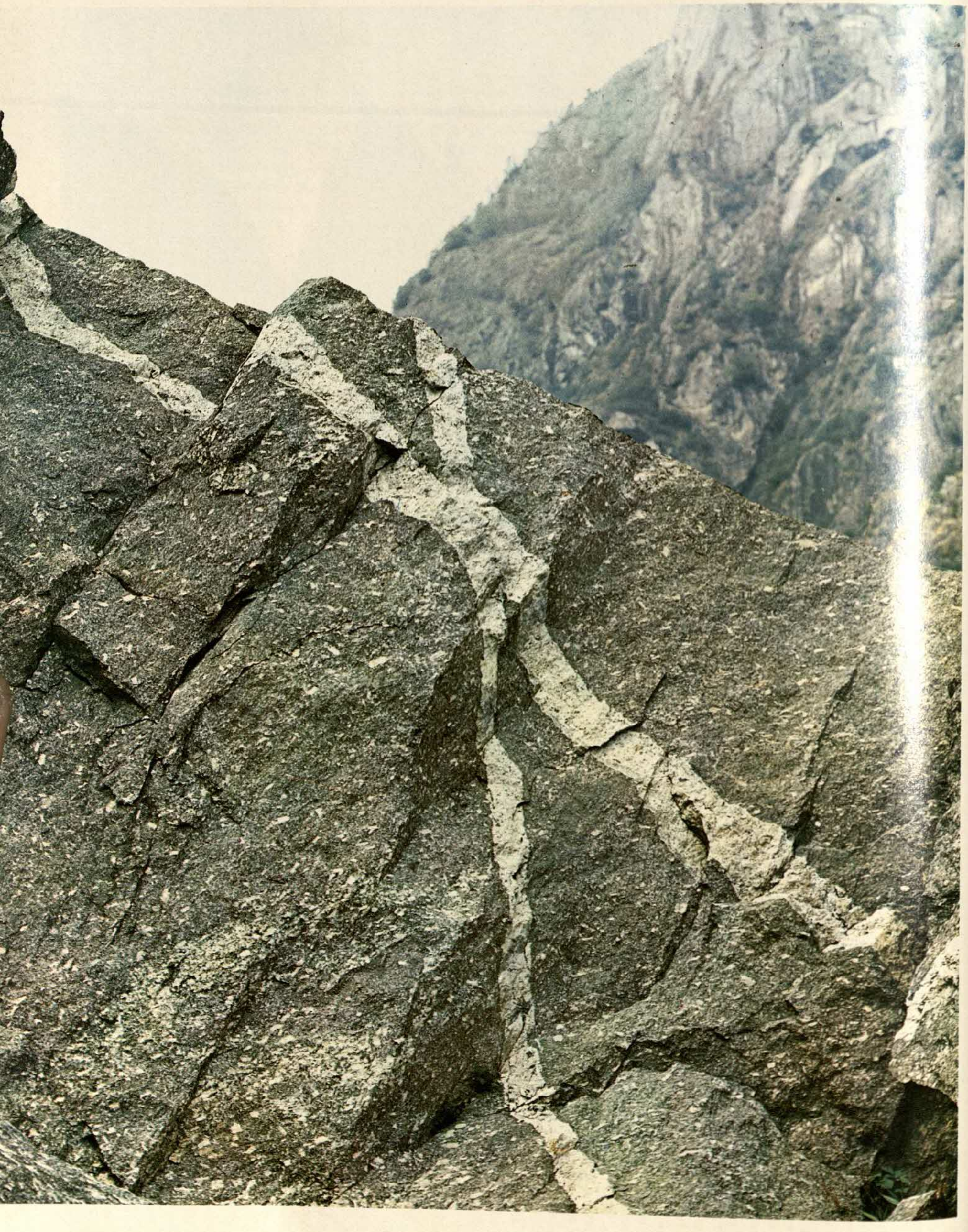
OPHIOLITHIC ERUPTIONS

Orogenic phenomena sometimes are caused by lateral thrusts that wrinkle rocky strata, bending them in some cases so intensely as to form folds that cover the strata lying alongside. The formation of these folds may cause crustal fractures through which magmatic masses of sima from the depths of the Earth are injected.

The term *ophiolite* comes from the particular nature of the rocks in which these magmas have solidified and from the rocks that are formed when the magmas are subsequently altered and partially transformed. In fact, the continuation of orogenic phenomena alters not only the form of the intruded masses, which undergo a great deal of bending, but also the crystalline structures of the intruded masses.

DISCORDANT INTRUSIONS

intrusions following lines of resistance



← **A STONE CROSS**—This photograph shows a very beautiful cross effect created by magmatic seams or dikes injected into granitic rock.

The study of magmatic intrusions arouses great interest among modern geologists. They want to know how the so-called country rocks (through which the magma opens a passage) have permitted, aided, or hindered the advance of the magma. In other words, they want to know how the magma penetrates the overlying rocks. It should be remembered that about 95 percent of the rocks of the lithosphere were formed by the solidification of magma. Geologists consider it extremely important to study how the magma of intrusions solidified, because it is then possible, even though difficult, to work back to the genesis of many other rocks.

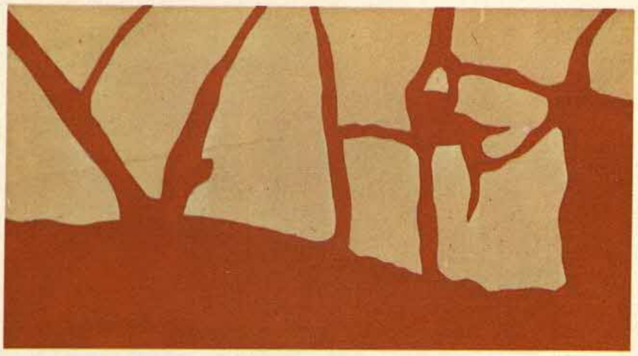
APOPHYSES

On the edges of a large intrusion, whether concordant or discordant, the magma often is injected into the rock surrounding it through passages of irregular shapes that cut across one another's paths. These passages are called apophyses. When the magma of apophyses comes into contact with the rocks into which it has been injected, it may chemically alter those rocks, and simultaneously be altered itself. This is possible because, at the high temperatures involved, many chemical elements are exchanged between the magma and the country rock. Geologists, therefore, are not surprised to find that the magma of an apophysis differs in chemical composition, and often in structure, from the magma in the main basin.

SEAMS

To most people, the term *seam* connotes a deposit or intrusion rich in useful minerals that can be extracted by mining operations. The magma forming seams is injected into fractures in the rock in a fairly short time. This material comes from around the magmatic chamber, where some components of the magma are easily separated from one another chemically. For this reason, the seams are made up of materials differing greatly from the average composition of the magmatic chamber. The materials of the seams are often useful minerals.

Seams or dikes are intrusions of magma along the fracture planes of the rocks that surround a magmatic chamber. These fracture planes are not necessarily either parallel to, or perpendicular to, the stratification planes of the rocks, and they may lie in all possible directions.



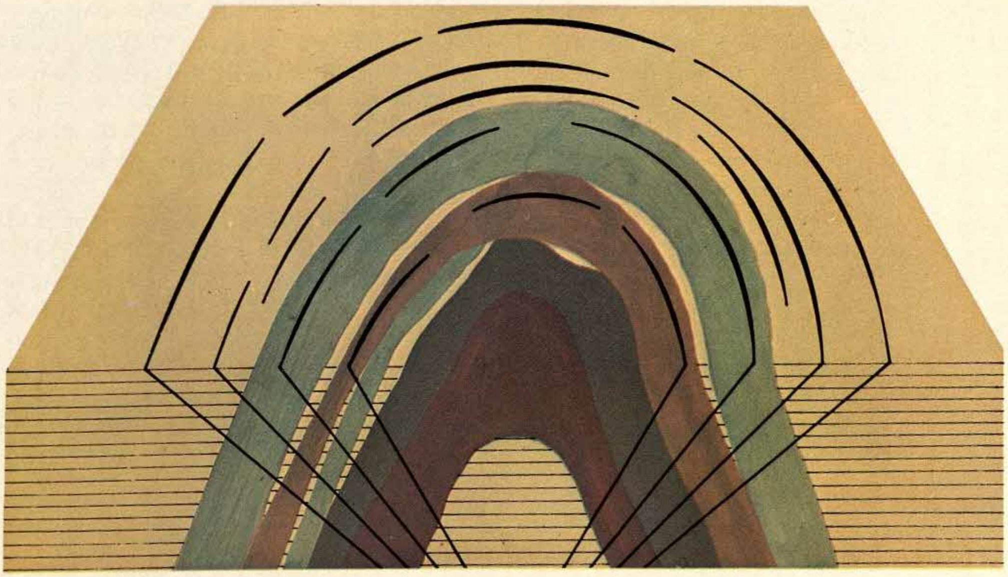
APOPHYSES — Often magma is injected into a pre-existing rock formation in the form of irregular branching arms called apophyses.

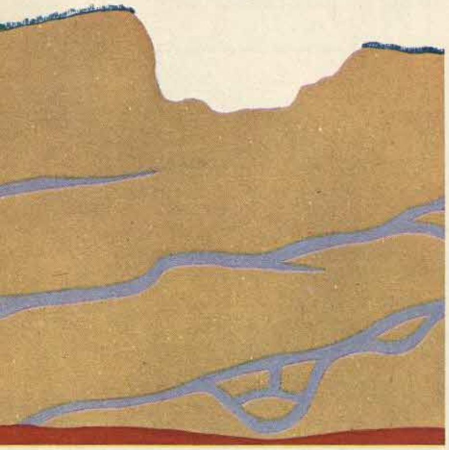
Magma under pressure tends to open a path in the direction that offers the least resistance. How is it, then, that seams have been formed independently of the lines of easiest penetration? This important problem can only be solved through a careful study of the outlines of seams, their extent, and their arrangement with respect to the main plutonic mass and the rocks into which they have intruded.

ASSOCIATIONS OF SEAMS

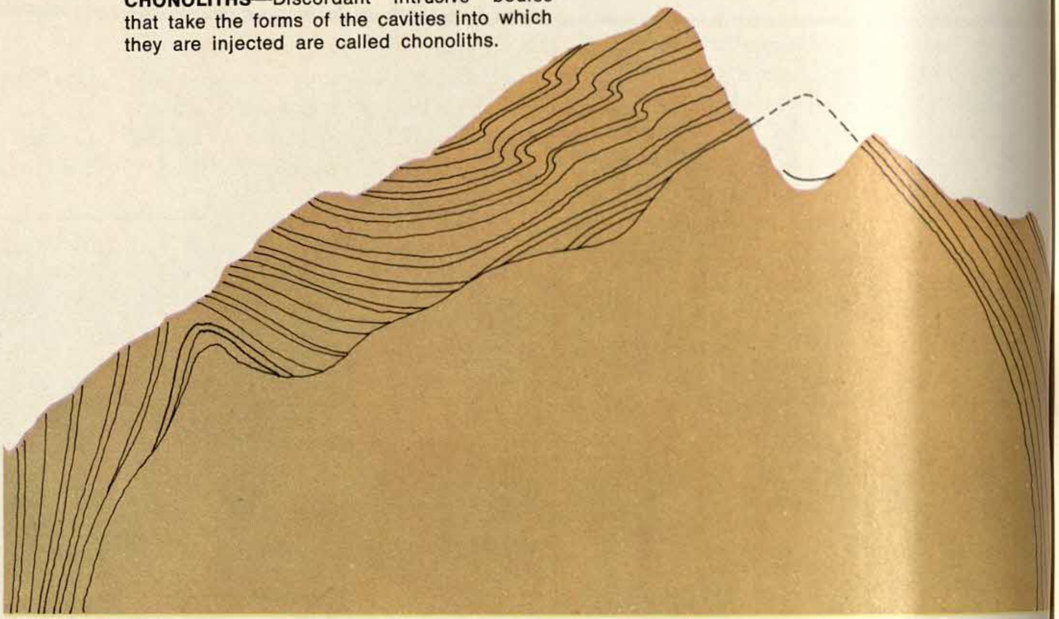
A seam is rarely found isolated. It is more often found in association with other seams. Seams can be found in a number of positions—in an irregular arrangement, a parallel or nearly parallel arrangement, a radial arrangement, or a ringlike arrangement.

STEREOGRAPH OF ANNULAR AND CONIC SEAMS—Under the highest part of a plutonic rock mass formed among stable rocks, magma may often make sinking phenomena possible. The sinking may split the plutonic rock into conic folds among which seams (indicated here in black) are formed. Some seams are extensive while others are extremely thin.





VEINS—The magmatic injections known as veins are distinguished from seams by their smaller dimensions, by their irregularity, and by the fact that their delimiting surfaces are not parallel.



CHONOLITHS—Discordant intrusive bodies that take the forms of the cavities into which they are injected are called chonoliths.

Sometimes, the examination of a limited area in which many seams have been formed in successive periods may lead to the conclusion that the arrangement of the seams is completely random or casual. However, an examination of a more extensive region will probably lead to the discovery of regularities in the arrangement of the seams. Where a region is furrowed by parallel seams, the rocks have been fractured by orogenic thrusts or local movements of rock masses under pressure from magma. Very likely these seams were produced by an extremely rapid injection of liquid magma into the fractures shortly after they were opened.

Seams are often arranged in rays around a pluton. Around a volcano, the pressure of magma in a conduit may have broken the surrounding rocks radially, permitting the magma to penetrate into them. The same thing may have happened around a very large plutonic mass at the time of its formation. In this case, the pressure of the rising magma may have created radial fractures. Such phenomena occur when the plutonic rock is completely buried under a deep stratum of rock; the seams rarely reach the surface.

In most cases, the underground phase of plutonic movement ends without the appearance of any signs on the surface. Sometimes an earthquake may result from the shifting of the rocks subsequent to the opening of fractures through which the magma was injected. The small earthquakes that occur rather frequently around volcanoes indicate that these fractures and injections are taking place under the surface.

Seams, with their more or less regular arrangement, can be encountered in the drilling of a well or the excavation of a mine; after a geologically lengthy period of time, erosion removes the strata covering the plutonic rocks.

When a plutonic block is lifted vertically, or sinks, fractures may occur. Consequently, seams may be arranged in a ring around the main plutonic mass, or they may be arranged in conical folds with respect to a point situated beneath the roof of the mass.

Some seams are extensive, while others are very thin and of modest dimensions. Between these two extremes exist many seams of intermediate size. The largest is the Great Dike in Rhodesia; it is about 500 km (about 300 mi) long and 3 to 12 km (about 1.5 to 7.5 mi) wide. Seams may be as much as a kilometer thick, but most frequently they are a few meters thick. "Seamlets" of small dimensions are found when magma fills the microscopic fractures that spread out through the rock from fractures in the main seam.

INTRUSIVE VEINS

Intrusive veins are magmatic injections whose dimensions are smaller than those of seams and whose delimiting surfaces are often branched but never parallel. Veins are frequently found in igneous rocks. In rocks formed by the solidification of a pluton, the magma—which is molten in the central part and solid on the outside because of its contact with cooler rocks—may be injected as veins into the part that has already solidified. These veins are distinguished from the rock associated with them by small but appreciable differences in the magma's composition from one point to another within the pluton.

CHONOLITHS

Among concordant intrusions are the laccoliths, intrusive bodies that have opened passages beneath horizontal strata, inflating and lifting them until a lens-shaped cavity has been formed. Sometimes magma opens a path in nonstratified rocks containing cavities or fractures that may become larger under pressure. Sometimes, the flow of magma breaks pieces of rock from the walls of the conduit through which it passes. The erosive effects of magma are also increased by the fact that the magma melts the rock through which it passes. This mechanism is operative in those irregularly shaped injections of magma that have no precise relation to the country rocks and that are therefore difficult to classify.

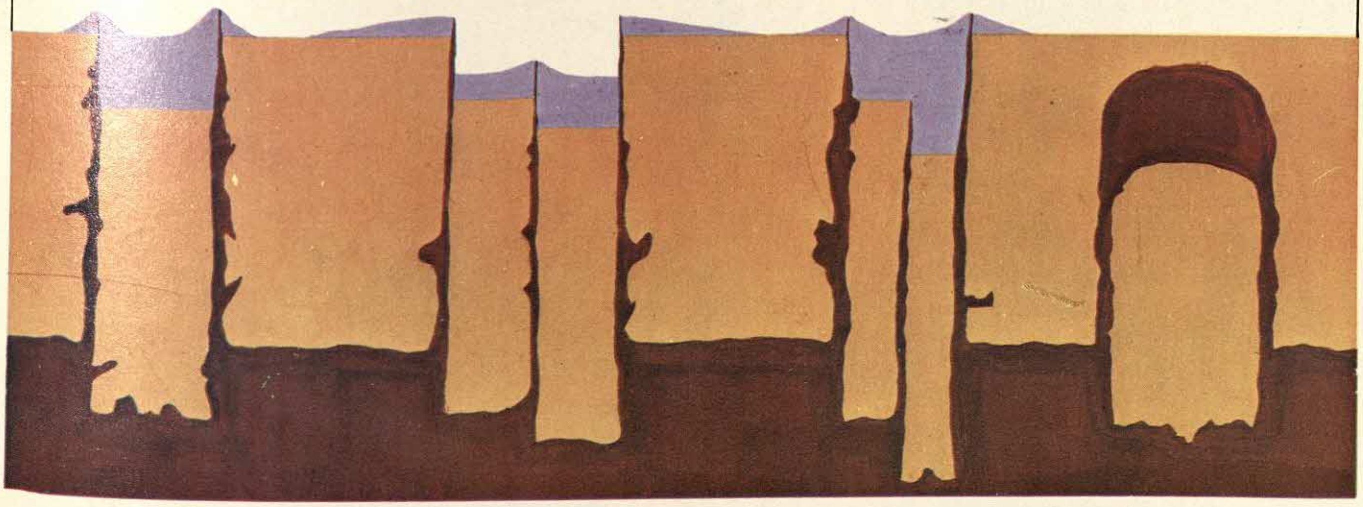
Geologists have found it helpful to classify the different types of intrusive bodies, because each of them is found frequently in this or that part of the Earth's crust. Knowledge of the various kinds of intrusions enables the geologist to identify the geological history of a given piece of ground, and such knowledge may even help the economic geologist in his prospecting.

Exposed intrusive bodies are most numerous in great mountain zones for two reasons: (1) the mountain belts have been zones of deformation, and abundant evidence indicates that igneous action is favored by crustal disturbances; and (2) great uplifts in mountain belts have set the stage for erosion to the depths at which plutonic masses have formed. The best displays of large intrusive bodies are found not in young chains such as the Alps, but in much older mountain units such as the Riesengebirge (Giant Mountains) of Germany, where the deep cores have been exposed by erosion for ages. Knowledge of intrusive igneous bodies has grown slowly by means of comparative studies—some in regions where erosion has brought to light only the masses that developed at shallow depths, and others in profoundly eroded belts. Beneath the growing mountain chains near the Pacific Ocean, intrusive action is in progress.

BLOCK STOPING

A thick stratum of rock may be eroded by magma and fall into the depths of the molten rock. Such a process is called block stoping. The shapes of the submerged rock blocks are shown in the illustration below, which shows how the sinking of the rocks may force the magma to the surface, producing eruptions. Moreover, a block of rock may reach as far as the surface of the Earth. In some cases, however, the phenomenon is entirely subterranean. The sinking then takes place as the magma rises to fill the cavity left by the sinking rock mass. Typical examples of this process are blocks of intrusive rocks shaped like giant cylinders with diameters of hundreds of meters. Their origins can be explained by this process.

BLOCK STOPING—This process occurs when a solid rock stratum is eroded by magma and falls down into it.



BATHOLITHS | the largest intrusive bodies known

Among all the types of plutonic rocks, the batholiths have the largest dimensions. For this reason, it is difficult, and sometimes impossible, to establish their forms. In fact, they extend downward to such great depths that their roots are unknown. Characteristically, batholiths intrude into other rocks without being influenced by the stratification, schistosity, or composition of those rocks. This kind of intrusion is said to be discordant, as opposed to concordant intrusions, which follow the paths of least resistance.

THE GREAT EXTENSION OF BATHOLITHS

The largest batholith in existence is located in the North American cordillera. It forms a large part of the coastal mountain chain that stretches from British Columbia to Alaska. It is about 2,000 km (about 1,200 mi) long and 200 km (about 120 mi) wide. This batholith has been laid bare by the erosion that has attacked the mountain masses.

Another enormous batholith constitutes the larger part of the coastal chain of the Patagonian Andes. It is 1,100 km (about 680 mi) long and 110 km (about 68 mi) wide, and it extends through southern Chile as far as Cape Horn. In the Alps, the most noteworthy batholiths are represented by the massifs of Mont Blanc, Punta Argentera, and St. Gotthard.

Plutons with smaller dimensions—on the order of 100 square kilometers, for example—are called stocks, even though they have the characteristics of batholiths. Many small batholiths are found in Italy, as well as a large number of plutonic stocks.

THE STRUCTURE OF A BATHOLITH

The rock formed from the solidification of the magma of a batholith is often so hard and compact that it provides excellent building and decorating materials. The surface that delimits the top or roof of the batholith frequently has a complicated, irregular shape. It obviously is made up of the encasing or country rocks, which extend downward at certain points into the mass of the batholith to form so-called roof pendants. Under the roof pendants, or even at some distance from them, fragments of the country rock may be completely immersed in the mass of the batholith. These fragments, called xenoliths—that is, foreign stones—are large blocks of rock that have been detached from the roof of the pluton and have sunk into the liquid mass until progressive cooling has prevented further sinking.

When the upper part of a batholith is stripped bare by erosion, its ramifications may appear on the surface, isolated from the main plutonic mass. These rocks are, therefore, called satellite masses; that is, bodies that belong to the plutonic mass as satellites.

The large magmatic mass of a batholith has usually taken a considerable time to cool. Around the edges of the mass, heat has been transmitted to the country rocks, altering their structure; in addition, elements may have been exchanged between the plutonic rock and the surrounding rocks. Therefore, aureoles of altered rocks frequently exist around the satellite masses and also around the whole plutonic mass; they are called metamorphic contact aureoles; that is, aureoles of rock transformed by contact with the plutonic mass.

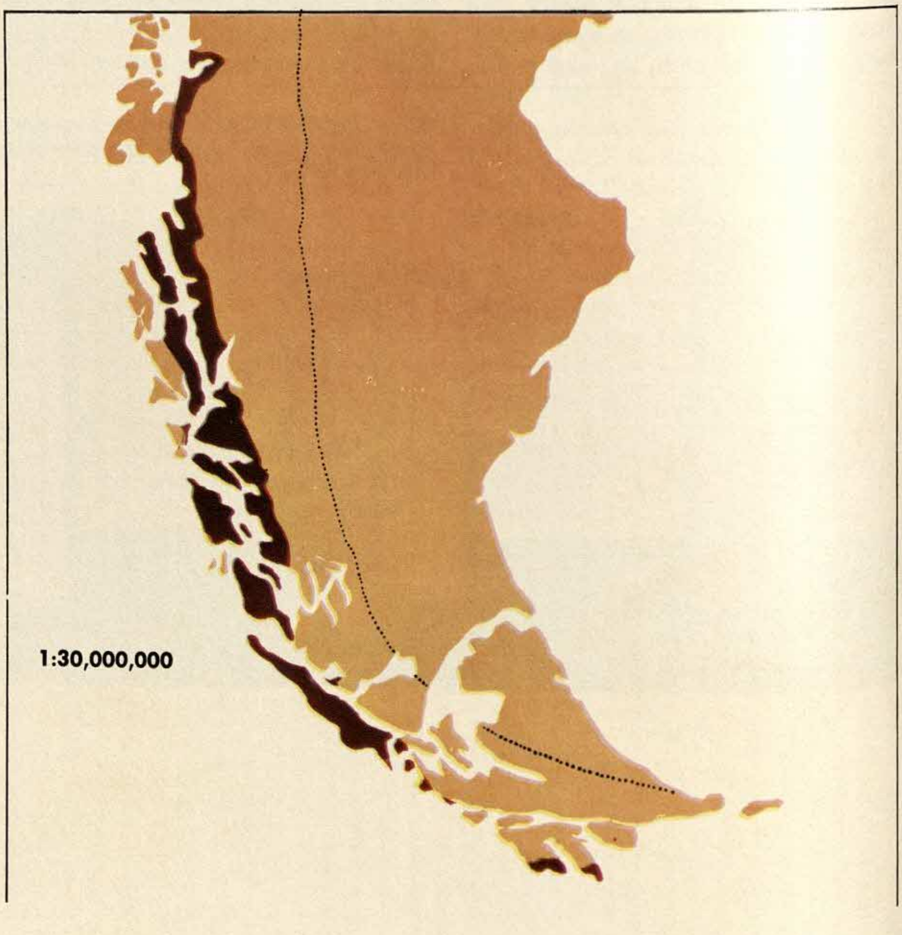
The upper part of a batholith may vary in thickness from hundreds of meters to some thousands of meters. A typical example is the upper part of the Erzgebirge batholith in Europe, which attains the extraordinary thickness of 6,000 m (about 20,000 ft).

BATHOLITHS AND THE GREAT MOUNTAIN CHAINS

It has already been noted that the great American batholiths are located parallel to the mountain chains of the North American and Andean cordilleras. The same observation may also be made in reference to other batholiths that are found associated with zones of intense orogenic activity. Studies reveal that the rocks encasing these batholiths have been folded extensively. It may, therefore, seem that orogenesis has favored the formation of the batholiths.

Various large intrusive bodies in the Italian Alps could be considered batholiths in the full sense of the word. However, it is thought that each of them is but a giant upward protrusion of plutonic rock from a colossal batholith that underlies almost a complete strip of the Alpine

THE PATAGONIAN BATHOLITH—This map shows the position of the batholith (dark) that extends parallel to the axis of the Andes chain in South America.



mountain chain; in other words, it is believed that these plutonic rocks represent a small part of an extraordinarily large batholith.

THE NATURE OF BATHOLITHIC ROCKS

The rocks that constitute a batholith derive from the solidification of magma. Their structure and composition vary considerably, according to the magma's chemical components and the conditions under which they cooled. Chemical analysis reveals, for example, that the rocks forming the batholiths of the Northern Alps are all similar in composition. This discovery supports the hypotheses concerning their common origins and the presence of a common subterranean root.

Chemical analysis also provides a means of identifying differences in the composition of the rock from one point to another in a batholith. For example, studies show that rocks of the upper part sometimes have a different composition from those lying farther down; they also show that the xenoliths have a composition identical, or almost identical, to the country rocks. Generally speaking, batholiths consist of granitic rocks.

THE ORIGIN OF BATHOLITHS

Only the upper part of a batholith is ever accessible for study; this part constitutes only a very small portion of the entire pluton. If it were possible to explore as far as the batholith's unknown root, it would be possible to learn something about its origin. Although such investigation is presently impossible, studies of various batholiths have suggested a number of hypotheses concerning the mechanisms of their formations. Unfortunately, none of them alone is capable of explaining the history of each batholith.

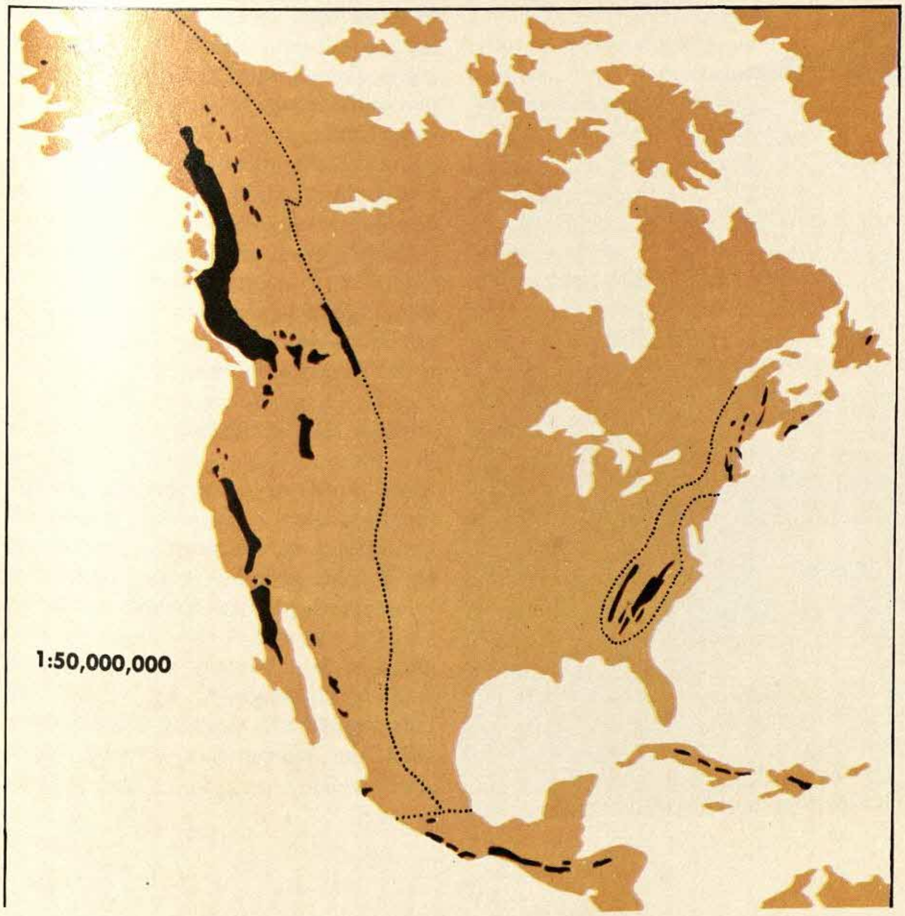
Two hypotheses are more important than the others. According to the first, batholiths are formed when preexisting rocks melt, and the magma undergoes a chemical modification. This phenomenon is called palingenesis, that is: the formation of new rocks by the re–fusion of former rocks deep inside the Earth.

The upper parts of some batholiths are encased in large rock strata that are difficult to melt and also difficult to absorb. Therefore, the heat rising from the depths of the plutonic mass has managed to melt only those rocks that have relatively low melting points, leaving almost intact the more refractory rocks that are included in the mass. This hypothesis, called magmatic stoping, may provide a good explanation of how the roof of a batholith is formed.

Another hypothesis has been formulated to explain the formation of the deeper part of the plutonic mass. The magma of a batholith is supposedly formed when deep rocks melt. The heat of this molten material then causes the overlying rocks to melt. The overlying rocks mix with those in the batholith, without substantially altering the composition of the latter. The deep magma, according to the hypothesis, therefore, opens a path for itself by a process of remelting and replacing the overlying rocks.

An acquaintance with all of these geologic phenomena provides a background that is helpful in studying the history of life on the Earth, the grandest phenomenon of all.

THE NORTH AMERICAN BATHOLITHS—This map shows the position of the largest known batholith, which forms the rocks of the greater part of the coastal chain and pushes inward into the North American continent. The map also shows the boundaries of the other North American plutonic masses; despite their size, these batholiths are small in comparison with the giant already mentioned.



FINE SECTION OF GRANITE — The granites are intrusive igneous rocks; in other words, they are rocks that have solidified at a great depth. They contain an abundance of silicon in the form of quartz, and they form a large part of the masses of most batholiths.

VOLCANIC ERUPTIONS | their role in the evolution of the lithosphere

Few sights on Earth can rival the beauty and majesty of a great volcanic mountain; and few geologic phenomena can result in the spectacular devastation that a large volcanic eruption may cause.

Of course, all volcanoes are not exactly alike; they differ in the structures that they form, in the amount of their activity, and in the nature and products of their eruptions. However, all volcanoes have one thing in common: a magma chanber or reservoir deep underground. The same forces that move the magma chamber or reservoir deep underneath the surface of the Earth also cause the magma to erupt onto the Earth's surface in the form of lava and solid ejecta.

The chemical characteristics of lava vary from one magma chamber to another. For example, the lava from Vesuvius differs in chemical composition from the lava erupted by a volcano situated in the center of the Pacific Ocean. The chemical composition of the gas phase of magma is not well known.

MECHANISM OF A GENERIC ERUPTION—A reservoir of magma is connected with the surface by means of a throat or conduit. Magma rises from the reservoir through the conduit to the surface, forced by the pressure of the gas contained in the magma itself. Around the lava vent an accumulation of erupted materials, called a volcano, is formed. Its composition differs from the composition of the rocks on which it rests.

The overflow of magma can occur in different ways, depending on how it reaches the surface. Sometimes a pluton of large dimensions is laid bare; magma flows out of its roof and spreads. Because the overflow of magma occurs over an extensive area, this phenomenon is called an areal eruption.

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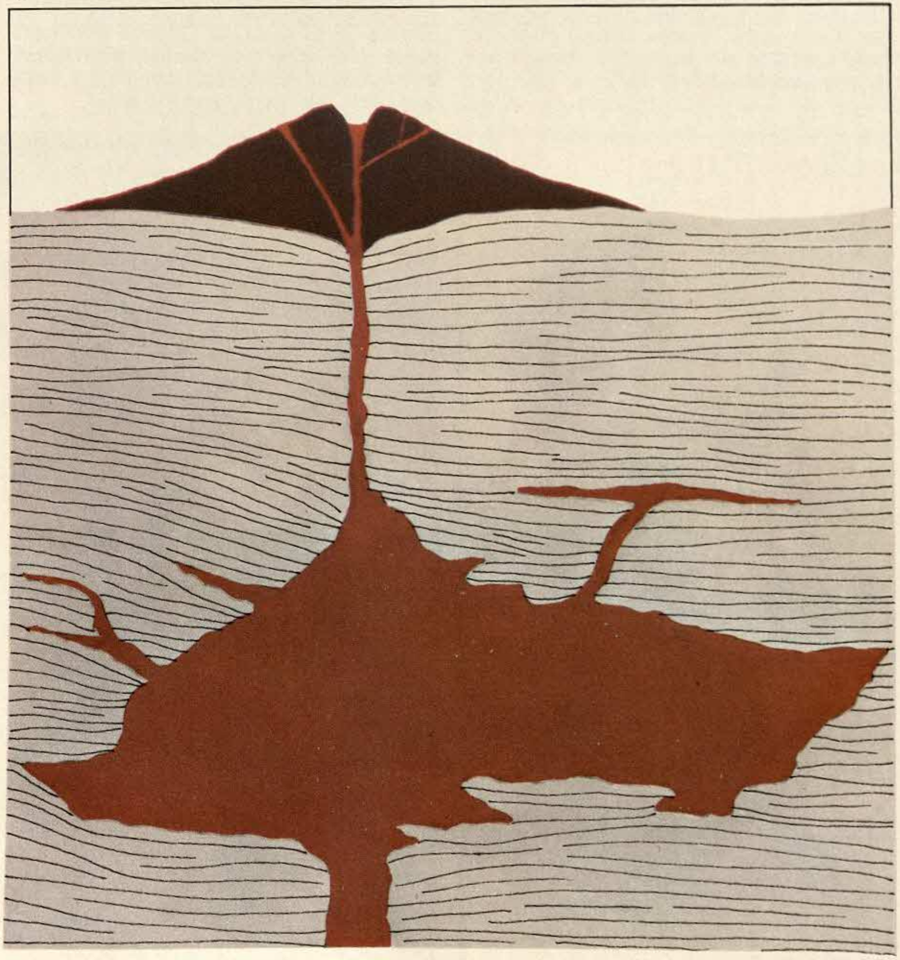


THE EVOLUTION OF VOLCANOES

A volcanic eruption is a temporary phenomenon, occurring when the magma rises from its reservoir to the surface of the Earth. When magma lava reaches the surface, after having made a path among the rocks, it pours out simply by expanding around the rim of the vent. The emission of lava occurs in several stages and continues as long as the magma chamber is filled with molten material; it then ceases all eruptive activity. Only the so-called secondary activities (emission of vapors and thermal waters) continue until the reservoir of magma is cooled further.

From a geologic point of view, the cycle of volcanic activity is generally of short duration, lasting from a few millions to tens of millions of years. However, the factors producing volcanic activity and the size of the magma chamber can sometimes prolong the cycle.

In Italy, the only active volcanoes are those that originated about a million or so years ago. However, some more or less prominent volcanic landforms and traces characterized by secondary activity, and dating back to more remote times, still exist.

Very likely there is no part of the Earth's surface that has not been the site of volcanic activity at some time in the past. Regions such as the British Isles that are not thought of today as volcanic have experienced violent and prolonged volcanic activity. At present, Indonesia is the most active area.

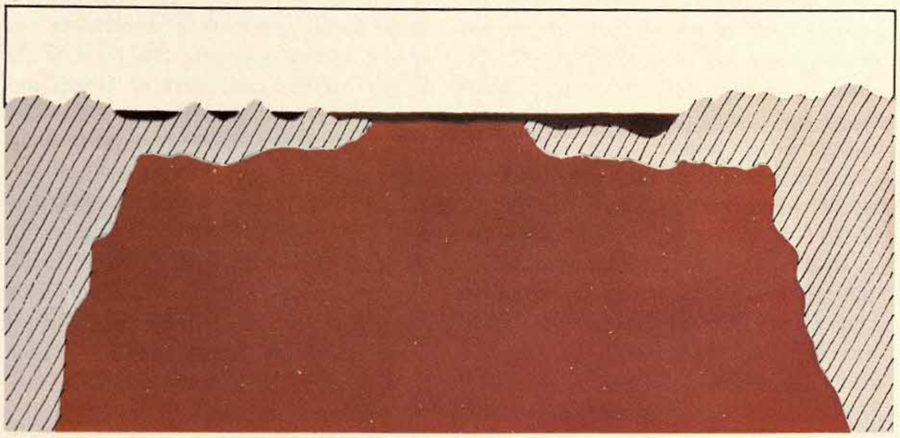
AREAL ERUPTIONS

Areal eruptions occur quietly, because the large opening for overflows prevents the buildup of extreme gas pressures in the magma chamber, pressures capable of causing explosions; therefore, it is said that the emission of lava occurs by quiet effusion. If, however, the emission of lava is accompanied by violent discharges and the ejection of solid materials, the phenomenon is said to be explosive.

AREAL ERUPTIONS—No areal eruptions have occurred within historic times. Nevertheless, geologists, through study of areas where areal eruptions have occurred in remote times, have been able to reconstruct the phenomenon. The illustration shows, in cross section, an areal eruption.

About a million years ago, in the part of the United States where Yellowstone National Park is located, a batholith formed; its magma came so near the surface of the ground that it partially melted the rocks of the roof. Then, magma flowed out of the batholith, invading a part of the surrounding area. The fact that the Yellowstone area is now affected by thermal phenomena (geysers and springs) indicates that the pluton has not yet cooled completely.

2



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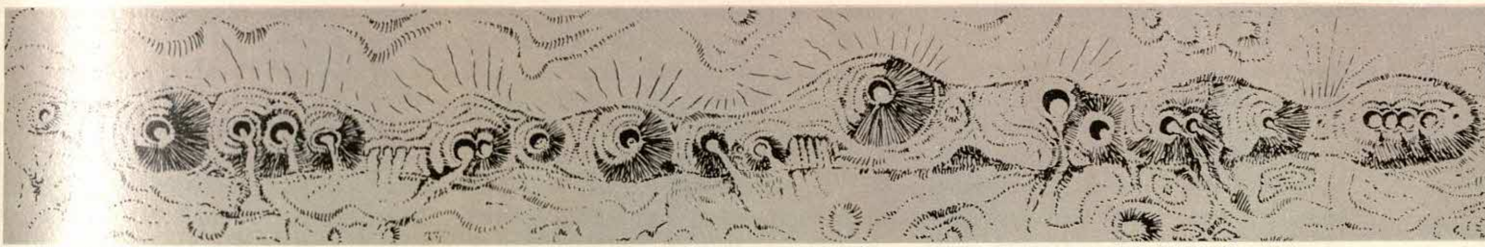

FISSURE ERUPTIONS—If magma comes to the surface through a fissure or a fault, lava flows from the volcanic vents that lie close together in a line, as shown in this illustration of a volcanic fissure at Laki in Iceland.

FISSURE ERUPTIONS

Some volcanic activities do not form mountains. Eruptions may occur through lava conduits that are nothing more than extensive fissures in the Earth's crust; some fissures attain a width of several meters. The eruptive phenomenon ordinarily consists of only one effusive phase, with the lava flowing quietly up the sides of the fissure, overflowing the rim, and descending to cover the surrounding area.

However, if the overflow is accompanied by a powerful explosive phase, part of the ground near the fissure can be hurled some distance; thus, the sides of the aperture become wider, forming a larger fissure. Geologists have discovered traces of an explosive eruption of this type that occurred in Iceland about a thousand years ago; the remains consist of a sort of fissure 30 km (about 19 mi) long. This eruption caused the overflow of almost 10 cubic km (about 2.4 cubic mi) of lava.

Between one eruption and another, lava has time to cool and solidify when it reaches the surface; the solidification of lava partly closes the aperture from which it flowed and permits the emission of a little gas and lava. Thousands of years may pass between phases of activity. With time, volcanic landforms—namely, a line of volcanoes as long as the eruptive fissure—form around the active conduits. Typical examples of active fissure volcanoes are those found in Iceland.

When the eruptive phenomenon diminishes in intensity, normal volcanic landforms rise along the fissures; if eruption resumes, it occurs first through the conduits of the volcanic landforms. The colossal flow of lava can then erode and destroy these landforms, carrying away their constituent materials with the spreading lava flow and permitting the magma to flow out directly from the fissure.

Often these solidified lava flows consist of rocks that are much more resistant than the rocks they have covered; during the course of time, the less resistant rocks beneath erode, leaving the lava block almost intact; it then stands out as a characteristic feature of the area. Some of the mesas found in the southwestern part of the United States and in Mexico are examples of such features. In ancient times great fissure flows spread out, covering the bottoms of several valleys. Although the lava was very hot, it was so viscous that it accumulated instead of flowing along the valley bottoms. When eruptive activity ceased, erosion slowly destroyed the surrounding mountains, which consisted of rocks that were less resistant to lava than the effusive rocks. While the mountains were being leveled, the flat block of lava in the valley bottom remained almost intact. A slight elevation of the entire region accentuated the rate of erosion, and water washed away most of the surrounding land, leaving the blocks of lava and the rocks beneath these blocks, which were protected by them. Today the landscape is flat for the most part, but is dominated by rare parallelepiped mountains consisting of less resistant rocks covered by a hard, highly resistant layer of igneous rocks. In this way the ancient valley bottoms have become mountaintops. A butte is similarly formed, but it is smaller.

LARGE ERUPTIVE PLATEAUS

Fissure flows, as described previously, spread to form a covering for the surrounding area. The blanket of effusive rocks consists of different layers, arranged one on top of another, often interrupted by layers of tuff, a material formed from the consolidation of volcanic dust and volcanic ash. Such a blanket of rocks constitutes a so-called plateau or flood basalt.

In Iceland and the Faeroe islands, basaltic rocks form plateaus 4 km (about 2.5 mi) thick; in the United States and in India, flood basalts almost 2,000 m (about 1 mi) thick are found. In Italy, a large plateau of effusive volcanic rocks extends along the arc that passes through Merano, Bolzano, Cavalese, and Trento; it is 1,400 m (about 0.8 mi) thick and extends over 4,000 km² (about 1,500 mi²).

At least 90 percent of all the rocks that have overflowed to form plateaus are basaltic. The largest flood basalt is undoubtedly the floor of the Pacific Ocean. Enormous quantities of basaltic magma have been deposited there, forming an extremely thick layer; the exact thickness is unknown. The most imposing basaltic flood layer whose dimensions are known is that covering the floor of the North Atlantic and part of Greenland, the Faeroes, the Hebrides, Northern Ireland, and Scotland. The basaltic cover extends over at least 2.5 million km² (about 1 million mi²) and is more than 1,000 m (about 3,280 ft) thick. In the Deccan region of India, flood basalts cover a surface area measuring about 650,000 m² (about 7 million ft²) and are almost 3,000 m (about 10,000 ft) thick. It is believed that effusive deposits continue under the waters of the Indian Ocean. The flood basalts of Paraná in Brazil cover a surface area of almost 1 million km² (about 400,000 mi²); in common with the aforementioned plateaus, they are the product of thousands of years of eruptive activity.

In other parts of the world many eruptive masses extend over tens and hundreds of square kilometers, bearing testimony to the great importance volcanic eruptions have had in the evolution of the lithosphere.

EROSION OF BASALTIC MASSES

Basaltic rocks are extremely compact and resistant, while the rocks surrounding flood basalts often are less resistant—or more erodable. Therefore, the basaltic mass eventually is found protruding from the surrounding ground. The characteristic structure of rocks formed by basaltic flows that have cooled rapidly thus can be observed readily. The basalt is fractured into hexagonal, regular, and upright prisms, arranged perpendicularly to the thickness of the flow. The erosion of one side of a fractured basaltic mass that lies horizontally reveals a large row of columns, such as the basaltic pillars in Fingal's Cave in the Hebrides, just west of Scotland.

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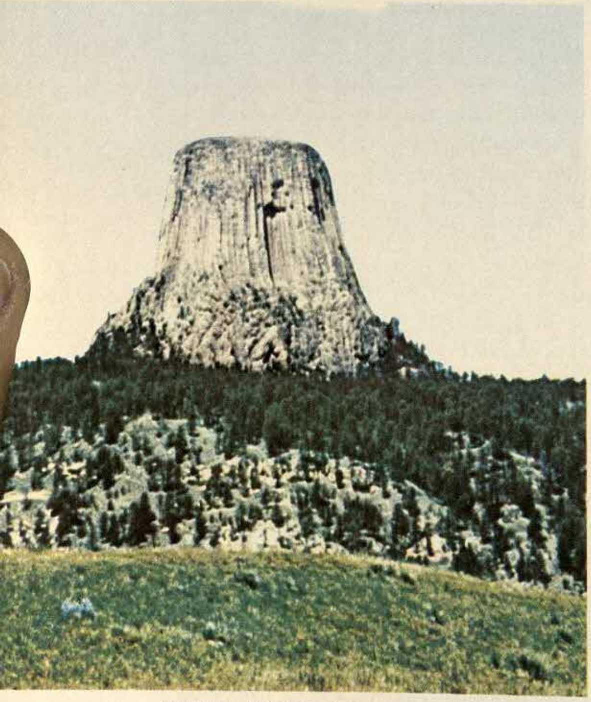

DEVIL'S TOWER—This gigantic igneous block in northern Wyoming is known as the Devil's Tower. Noted for its fluted appearance, this rock of volcanic origin has been designated a national monument.

INVERSION OF VOLCANIC RELIEF—A thick layer of resistant lava spread over a surface consisting of less resistant rocks (Illustration 5a). Subsequently, erosion wore away the less resistant rocks, leaving the lava block intact. In this way, the lava block emerged in relief as a characteristic feature that protects the underlying rocks (Illustration 5b). These small plateaus typically are called mesas.

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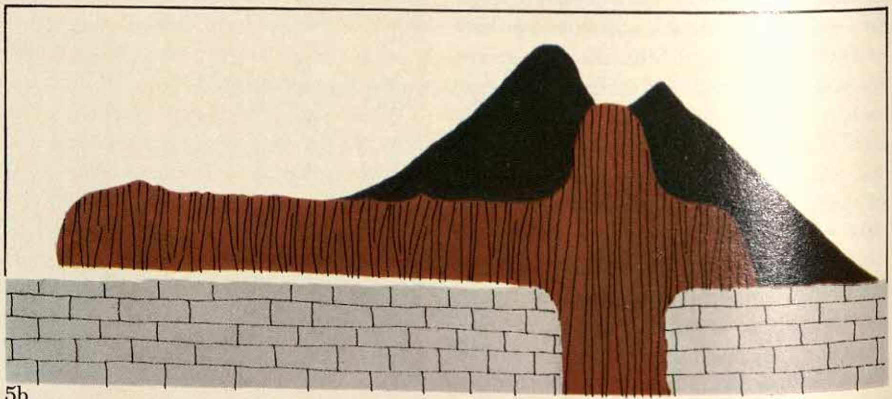

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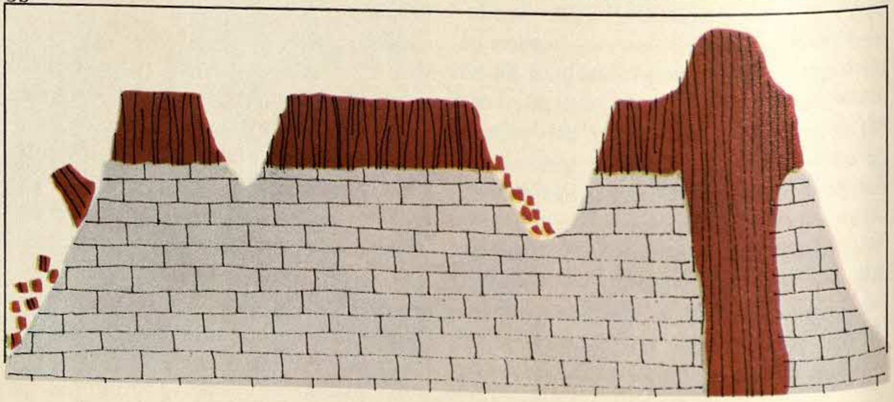

CENTRAL VOLCANIC ERUPTIONS

typical volcanic structures

When a single throat or conduit constitutes the means of communication between the magma chamber of a volcano and the surface of the Earth, eruption occurs at the point where the throat emerges and the products of eruption flow out around this opening. This type of volcanic phenomenon is called a central eruption.

EXPLOSION CRATERS

Explosion craters are small volcanic landforms produced by explosive activity. Ordinarily, volcanic activity is divided into an explosive phase and an eruptive phase. The explosive phase generally precedes the eruptive phase; that is, the vapors accumulated at the top of the magma reservoir are emitted before the magma.

In eruptions that produce explosion craters, the activity is limited to an explosion, a violent emission of gas and perhaps some powdery or granular materials that tend to erode the crater, making it wider. No volcanic landform builds up around the vent of an explosion crater, because most of the products of eruption are gases that disperse into the atmosphere. Explosion craters are sometimes called embryonic volcanoes.

In the Eifel region of Germany, lakes are formed by the accumulation of rainwater in explosion craters. These lakes, called maars, have diameters ranging from 300 to 2,500 m (about 1,000 to 8,000 ft). Other European volcanic craters are located near Stuttgart in West Germany. In Italy, craters are found in the Euganean hills, the Berici hills, and the upper Veneto region.

LAVA DOMES

When viscous lava comes into contact with air, it cools and solidifies. In some eruptions, fluid lava is still hot under a semihard outer crust. Continuing to rise from the magma throat or conduit, the lava swells the crust built up by previously hardened lava. In this way a sort of semirigid lava bubble or dome forms and continues to expand. If the crust cracks during expansion, the liquid lava overflows this crust, cools on contact with the air, and becomes a new layer of crust welded to the underlying one. The dome may attain several hundred meters in both height and width. However, this mechanism cannot produce further growth, because the magma has become partly solidified, has lost pressure, and no longer has the force necessary to expand the dome.

The most famous lava domes are found on the island of Hokkaido in Japan, on the Greek island of Santorin, on the island of Martinique in the West Indies, in the Auvergne region of France, and in Lassen Volcanic National Park in the state of California.

SOLID PROJECTIONS

A volcano formed by the emission of a solid spine-like block rather than by the emission of gas, dust, or liquid lava, is an impressive sight. The pressure of the magma is so great that it overcomes not only the enormous weight of the spine, but also the great friction between the spine and the conduit walls. Mount Tabor on the island of Ischia is a solid projection; it was produced by volcanic activity during a preceding era.

CONSTRUCTION OF VOLCANIC LANDFORMS BY MEANS OF LAVA FLOWS

Typical volcanic cones are formed by the accumulation of successive lava flows. However, products of explosive activity also accumulate on volcanic slopes.

When water or ice erodes a volcanic landform, the layers of materials that have been deposited by volcanic action are cut away, revealing the eruptive history of the volcano. Lava flows can produce different kinds of landforms, depending on the compositions of these flows. Lava with a high content of silicon oxides is viscous because of the high melting point of its components. Such lava flows with difficulty and, therefore, remains near the volcanic vent, forming a cone with steep slopes.

VOLCANIC CRATER—The structure shown below of a small Icelandic crater is typical of volcanic landforms created by a single exposion. **KIMBERLEY PIPES**—The most famous explosion craters are the Kimberley Pipes in South Africa, shown diagrammatically here. These pipes are filled with kimberlite, a variety of peridotite, a rock formed by the solidification of magma. Diamonds are found imbedded in the rocks of these pipes.

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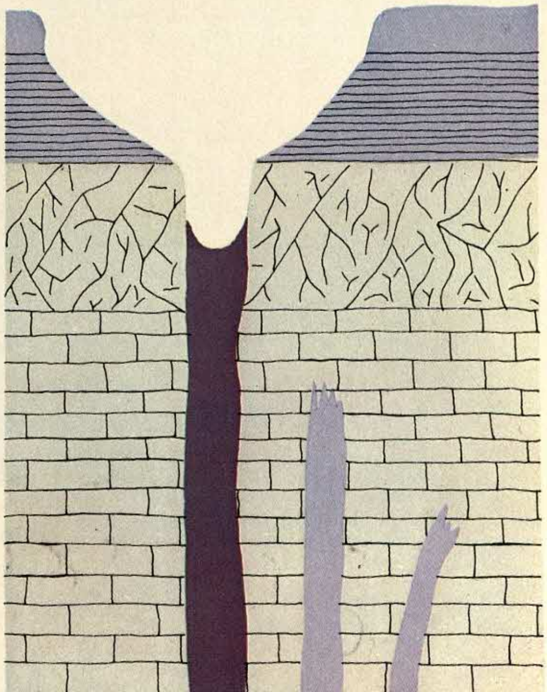


In contrast, basaltic lava is extremely fluid and flows easily and rapidly. Lava from Mount Etna, for example, sometimes travels a distance of 30 km (about 19 mi) from the volcanic vent. The extremely fluid lava of some volcanoes in the Hawaiian Islands flows to a distance of over 50 km (about 30 mi) and can attain speeds of 20 km (about 12 mi) per hour. Volcanoes that erupt extremely fluid lava rarely have explosive phases; their products flow easily, and lava accumulates around the vent, forming a very wide cone called a shield volcano.

The most common type of volcano is probably the composite volcano in which explosive and eruptive phases alternate. A composite volcanic cone is composed of alternating layers of unconsolidated and consolidated materials. For this reason, it is also called a stratovolcano or a stratified volcano. Typical examples are Mount Etna (3,269 m—about 10,700 ft), Tenerife (3,716 m—about 12,200 ft), and Fujiyama (3,776 m—about 12,400 ft).

When the composite volcanic cone has reached a sufficient height, the lava under pressure in the throat opens a path easily along a bank of tuff, which offers less resistance than the main throat, particularly if the conduit has been obstructed by a plug of solidified lava. In the latter case, lava reaches the surface by way of secondary vents on the slopes of the volcano.

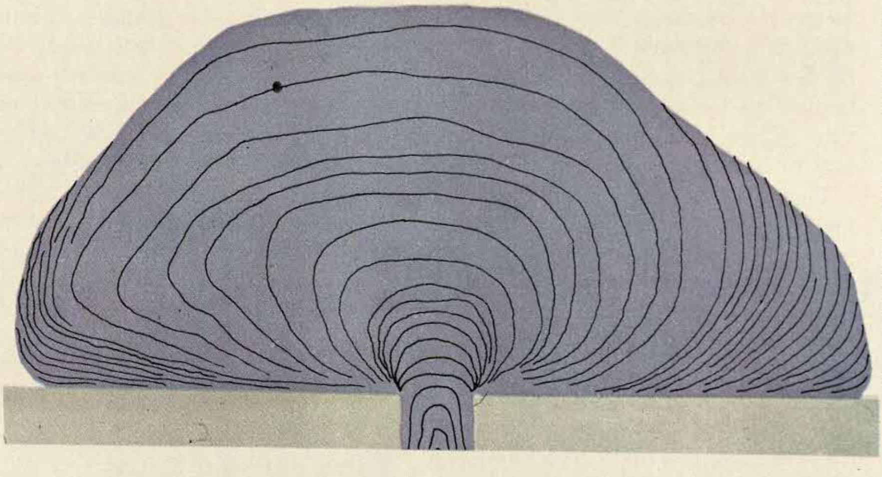
Newly erupted material accumulates around the vents, forming new cones, called subsidiary or satellite cones. A subsidiary cone may grow higher than the original cone or may even destroy it. Vesuvius, for example, destroyed the crater onto which it was grafted; the remains of the original cone form Mount Somma.

If the eruption of solid and gaseous products is violent, the volcano may partly collapse, because the substructure can no longer support the entire volcanic landform. The vent of the explosion crater, which connects the magma chamber with the surface, then widens in the upper terminal section to form the crater of the volcano. This crater is circular in almost all volcanoes.

CALDERAS

Often eruptions produce vast collapses in the areas surrounding volcanoes. In these cases, depressions of considerable size, called calderas, are formed. Calderas sometimes fill with water and become lakes. (Crater Lake in Oregon is an example of a caldera transformed into a lake.) Volcanic activity persists, and the volcano continues to be active. However, the cone is smaller than the caldera and is located at a point inside the caldera, but not necessarily in the center. A caldera with partially collapsed walls is known as a cirque.

3a



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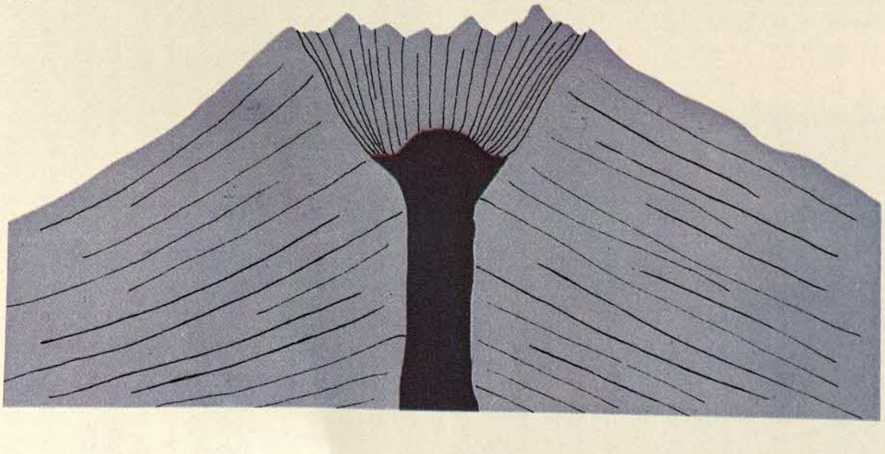

LAVA DOMES—Lava domes are formed by the accumulation of extremely viscous lava. The illustrations show a bulbous dome formed by the overflow of viscous lava (Illustration 3a), and a pluglike dome that solidified inside the crater of a volcano (Illustration 3b).

PELÉE SPINE—In 1902, during the eruption of Mount Pelee on the Island of Martinique, a lava dome 400 m (about 1,300 ft) high was formed in the crater of the volcano. This dome was then pierced by a solid lava spine that collapsed when it reached a height of 500 m (about 1,640 ft).

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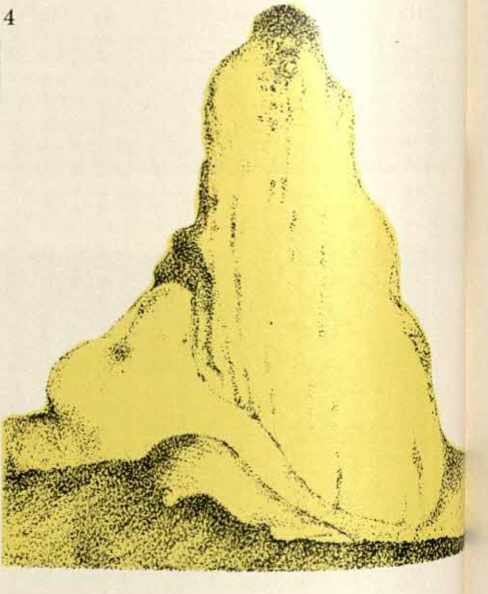


THE MECHANICS OF VOLCANIC ERUPTIONS

What causes magma to be forced up through volcanic conduits, to overflow, break up rocks, explode, and bring about destruction? What are the mechanisms of eruption?

Basically, there are two types of volcanic eruptions: passive eruptions, produced by outside forces acting on the magma, and active eruptions, caused by phenomena within the magma itself.

Studies of the Earth's crust indicate that it is mobile. Certain (tectonic) forces can move mountains, bending layers of rock and breaking them when they resist.

Without the involvement of tectonic forces, which determine the structure of continental masses, the passive squeezing of magma can be simply explained by the principle of Archimedes. Suppose that the roof of a magma chamber fractures and the fragments fall into the magma below. For them to float, the magma must rise to fill the spaces between fragments, and the specific gravity of the magma must be higher than that of the fragments. Often the specific gravity of rocks in the lithosphere is greater than that of the magma; therefore, the blocks of rock sink.

In certain cases, even though the specific gravity of the magma is greater than the rocks it sustains, the magma is still pushed upward through cracks into the rocky masses above because it contains great quantities of dissolved gas in the form of bubbles. This highly compressed gas is much heavier than air, but lighter than magma. A magma thus is composed of molten rock and bubbles of light gas, and its specific gravity is greater than that of a magma mass that simply contains gas in solution.

Under these conditions the magma is no longer capable of supporting the rocks above; these heavier rocks sink into the magma, which is thus forced by the weight of the rocks to rise through the cracks to the surface. This is clearly a phenomenon in which the magma acts as a passive agent; that is, it does not furnish the force necessary to move and erupt.

To understand how magma can take an active part in the process of ejection it is necessary to look into the phenomena that occur during the cooling of a volcano's reservoir of magma in the magma chamber.

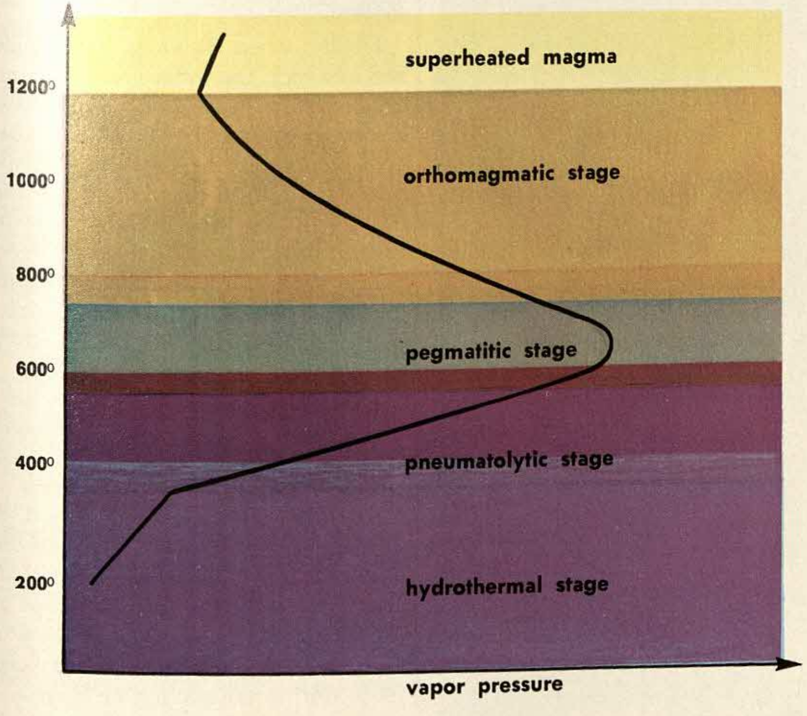
COOLING OF MAGMA

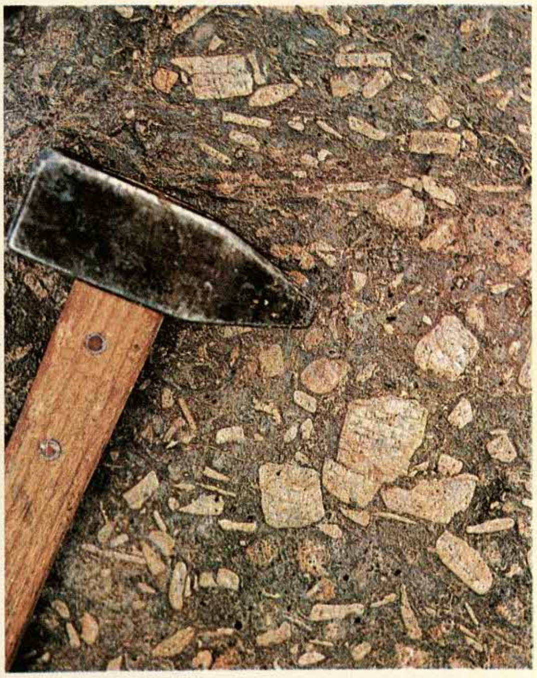
Magma is a molten mixture containing almost all chemical elements in the same proportions as they are found in the Earth's crust.

In a volcanic magma chamber, at the depth from which magma can rise to the surface, the temperature is about 2,000° C (3,632° F); under these conditions magma is extremely fluid. The elements comprising it are, for the most part, in compound form; for example, the metals are combined with oxygen to form oxides. If the temperature falls below 1,200° C (2,192° F), the part that has the highest melting point solidifies. Oxide molecules combine with other elements to form more complex molecular structures. Minerals in erupted rocks are composed of these molecules that formed by the simple cooling of magma.

Many of the components of magma are gases such as water vapor, helium, and carbon dioxide. These substances are not separated from the magma mass in the form of bubbles; instead, they are dissolved in the magma, just as carbon dioxide is dissolved in soda water. Ac-

COOLING OF MAGMA—The graph shows how the pressure of the dissolved gases in magma is dependent on the temperature (given in degrees Celsius) of the magma.





CONSOLIDATED MAGMA — Magma erupted from volcanoes, despite its high temperature, sometimes contains crystals of minerals that have already been consolidated, as may be seen in this lava fragment from Kenya in eastern Africa.

cording to the physical laws governing the behavior of gases, the quantity of gas that can be dissolved in magma is not unlimited. At a certain point the magma can no longer absorb gas; then it is said to be saturated. However, under different physical conditions, the quantity of gas dissolved in the liquid can be increased or decreased; the colder the liquid, the more gas it can absorb. Knowledge of gas laws is useful in studying the behavior of cooling magma.

STAGES IN THE COOLING OF MAGMA

At temperatures above 1,200° C (2,192° F), magma can maintain a certain quantity of gas in solution. Therefore, if the magma in a reservoir is above that temperature while it is cooling, it progressively holds back the dissolved gases it contains and exerts progressively less pressure on the walls of the magma chamber. During this phase of cooling the magma is incapable of producing active eruptions; if eruptions occur, they do so because the magma is "squeezed" out of the chamber by tectonic forces. Magma above 1,200° C is called superheated magma. At a temperature of about 1,200° C, some of the components of magma begin to solidify. This explains why the magma mass can contain crystals in suspension or why crystals can accumulate gradually on the chamber floor.

At this stage in cooling, the magma that is still liquid is capable of containing a greater quantity of dissolved gases. Because the magma is solidifying, the liquid part decreases progressively; nevertheless, it is forced to contain the same amount of gas, which tends to escape from the mass. The gas exerts more and more pressure against the walls of the magma chamber. During this phase, magma is capable of active eruption; when it begins to cool, the pressure it exerts against the walls of the chamber increases. The walls can no longer sustain the pressure; they crack, allowing the magma to push its way out. The pressure in the magma chamber decreases rapidly because part of the magma has escaped. Gas escapes suddenly from the magma, which increases in volume and, rising through the conduits, is erupted.

At the same time, another phenomenon occurs. The magma, filled with bubbles, is no longer capable of supporting the blocks of rock. They tend to sink into the magma, pushing it upward along the cracks between one block and another. The push against the magma is thus passive, although it is responsible for making the molten rock rise.

This phase of cooling, in which magma is capable of an active eruption, is called the orthomagmatic stage; it occurs at temperatures between 1,200° C (2,192° F) and 750° C (1,382° F); under 1,200° C, crystallization begins—that is, the atomic groups contained in magma reunite, combining according to complex rules to form mineral nuclei. For example, the groups formed of silicon and oxygen can reunite to form quartz. If the process continues, the minerals take on the appearance of crystals.

During the orthomagmatic phase, crystallization occurs throughout the entire magma mass and forms a considerable quantity of solid material. However, crystallization produces a great quantity of heat, slowing the cooling process.

Most of the magma crystallizes at between about 750° C (1,382° F) and 550° C (1,022° F). The quantity of liquid decreases considerably; therefore, even though the temperature falls, the vapor pressure of the dissolved gases, and consequently the pressure that the magma exerts against the chamber walls, increase. This stage in cooling is called the pegmatitic stage. The high pressure of the magma mass during this stage causes cracks to form around the magma chamber, but the cooled and viscous magma spreads with great difficulty.

At even lower temperatures, consolidation is complete. The liquid part—or at least the part that can contain dissolved gases—decreases and disappears. The gases dissolved in the magma seek a way to reach the surface, either opening a path by means of explosions (that are not followed by lava flows), or by seeping through the ground slowly. These are the last stages in the life of a volcano. During this phase, called the pneumatolytic stage, explosions or destruction of the eruptive apparatus can occur; however, these manifestations are not followed by a lava flow—that is, by a constructive process.

Finally, when the magma has solidified into rock, the water vapor—the principal magmatic gas—undergoes a change of state, becoming liquid water. This happens because the temperature has fallen below the critical point: 376° C (about 708° F). In this phase, called the hydrothermal stage, no eruptions occur. Vapors rise or thermal waters gush forth from the area in which the volcanic apparatus arises. At this point the volcano's activity ends and the magma chamber cools.

Until a few decades ago, it was believed that eruptions occurred because underground water suddenly reached the magma reservoir of a volcano, was vaporized by the heat, and forced the magma out of the volcanic conduit. However, only the physical behavior of magma during the cooling process can explain the phenomenon of active eruptions and the possibility of their occurrence during the cooling of magma.

GIGANTIC ERUPTIVE LANDFORM—The photograph is of the extinct crater of Mauna Kea, the highest mountain in the Hawaiian Islands. The crater, filled with water, is called Green Lake.

TYPES OF VOLCANIC ACTIVITY | classifying eruptions

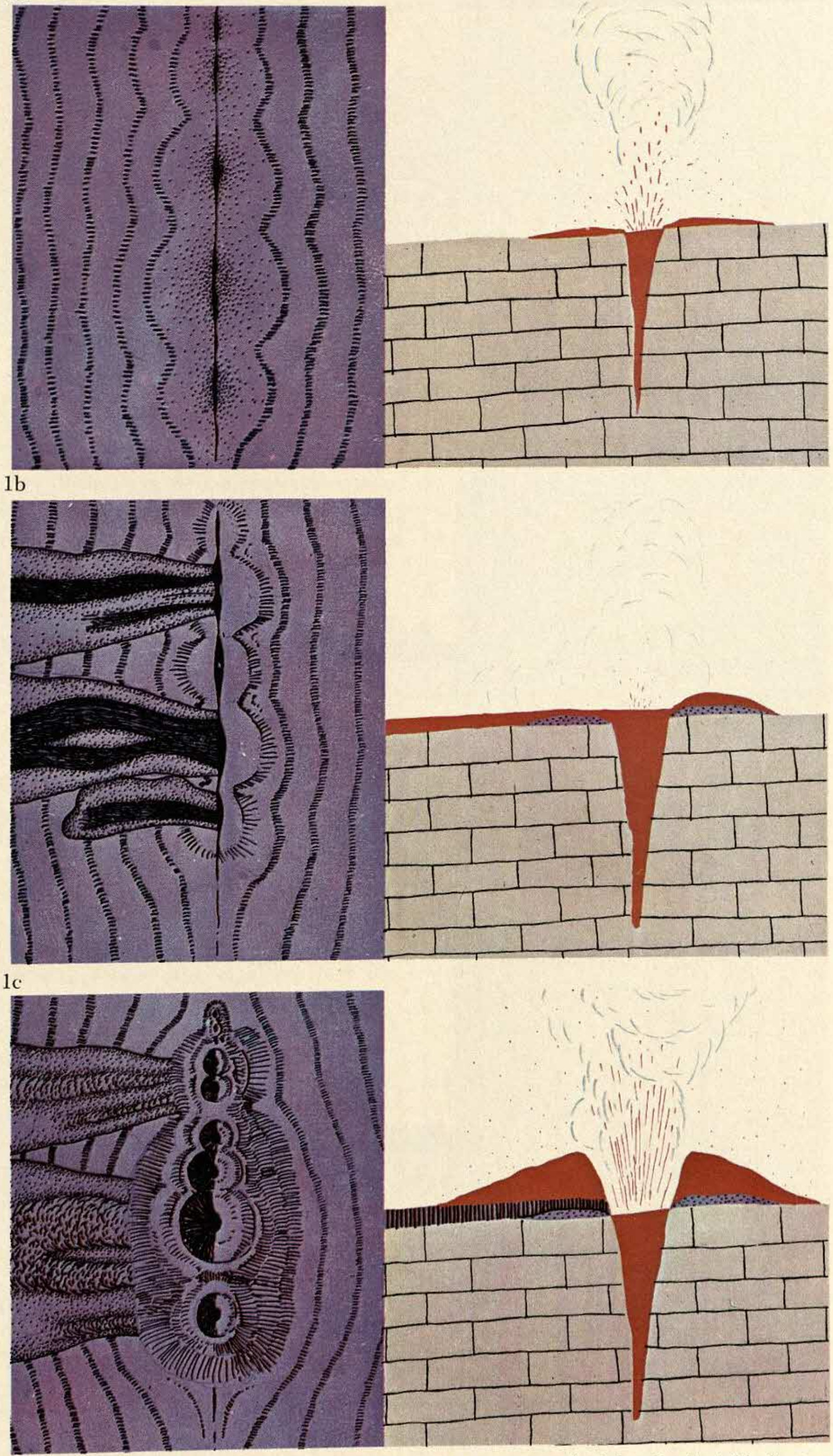
Volcanoes vary in the form and composition of their erupting mechanisms and in the type of volcanic activity they exhibit. Volcanic activity varies with different kinds of magma and with differences in the temperature of the magma reservoir; therefore, a volcano may, at different times, have different types of eruptions.

HAWAIIAN ERUPTIONS

A Hawaiian-type eruption usually occurs without an explosive phase. The lava is always very fluid, both because of its extremely high temperature and because of its chemical composition. Such lava solidifies chiefly into basalt and similar rocks and contains very little of the siliceous materials that tend to increase the viscosity of the lava. Gases escape readily from the lava, causing the molten rock that reaches the surface to boil gently. The accumulation of pressure in the magma chamber or in the volcanic throat permits the magma to rise and flow over the surface, where it solidifies slowly. The high temperature of the magma rarely produces a volcanic plug. Hawaiian-type flows are typical of volcanoes in the central Pacific. These volcanoes, which are fed by deep, fluid reservoirs of magma, are also called shield volcanoes, because they form broad, relatively flat and somewhat dome-shaped landforms.

STROMBOLIAN ERUPTIONS

Another type of eruption is named after Stromboli, a volcano in the Aeolian Islands in Italy. Such an eruption is characterized by a somewhat viscous lava. The lava is erupted with difficulty and is forced to rise by enormous volcanic gas pressures. Strombolian eruptions often are accompanied by violent explosions in which solid materials, such as lapilli and volcanic bombs, are ejected. The solid ejecta accumulate around the crater, while the viscous lava solidifies during the process of eruption (or shortly thereafter) and remains on the slopes of the volcanic mountain, descending with difficulty. As a result, the volcanic cone has steep slopes. Alternating eruptions of lava and pulverized materials or lapilli form alternating layers



RECONSTRUCTION OF A MASSIVE FISSURE ERUPTION—When a geologist observes a section of igneous rock, consisting of alternating layers of tuff and coherent rock (such as basalt), he can easily determine that this formation resulted from successive explosive and effusive eruptions. However, it is no simple feat to reconstruct the history of a massive

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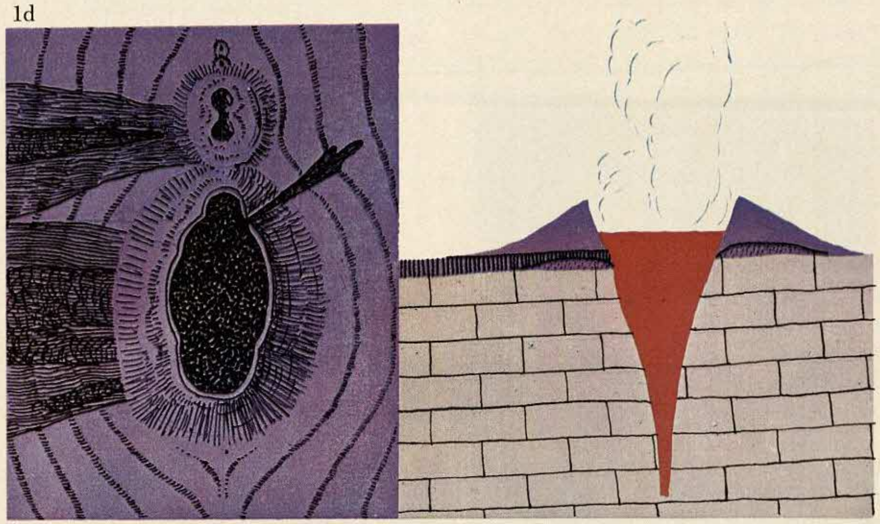

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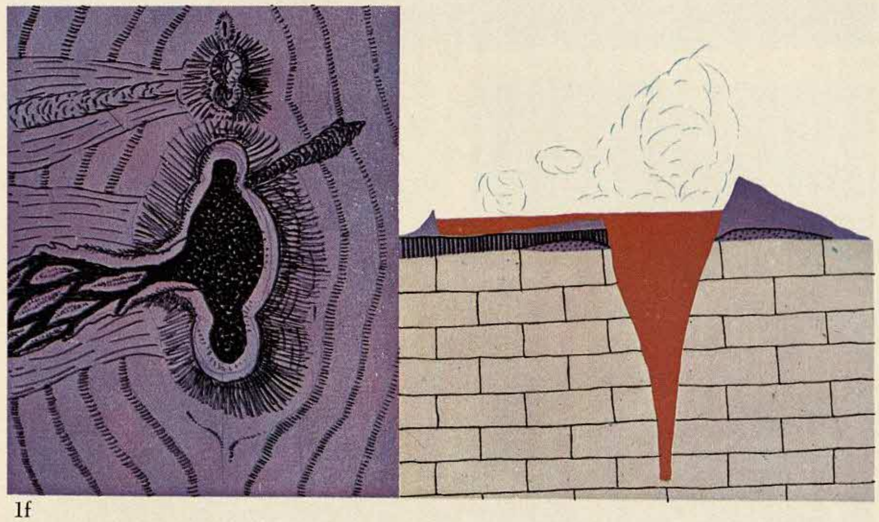

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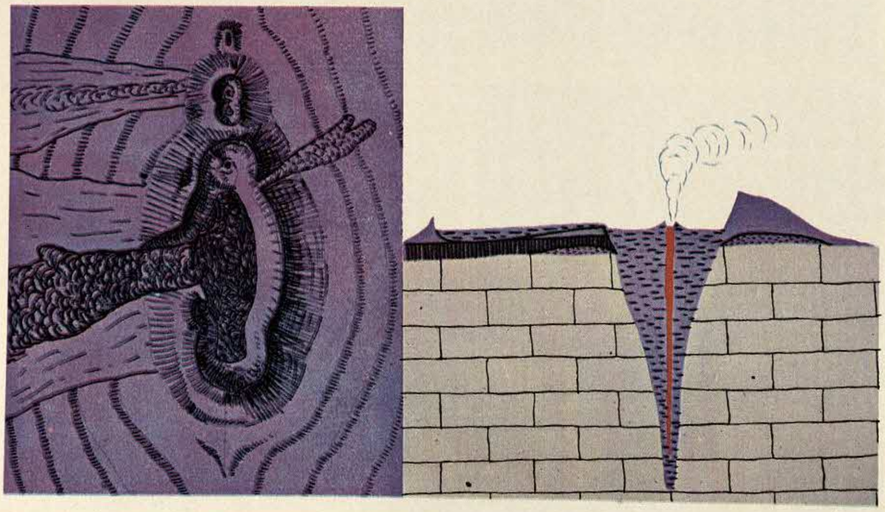

fissure eruption following its various phases. Nevertheless, the history of the fissure eruption that took place on the island of Threngslaborgir in the Myvtan region of Iceland has been reconstructed. This series of illustrations outlines the course of the eruptive phenomenon.

First, the ground was violently shaken. A fissure opened (Illustration 1a), emitting extremely fluid magma that lost some of the gas it contained. The fissure was widened by the many explosions that occurred, and much material was erupted in the form of bombs, lapilli, and rock fragments.

Then, the extremely fluid magma which had a high temperature and a still considerable gas content, rose to the surface and spread over vast areas (Illustration 1b). The gas that escaped during solidification formed bubbles inside the lava.

Next, the magma remaining in the reservoir freed itself of gases, which were emitted in great quantity (Illustration 1c). The gases emerged with explosive violence, tearing lava from the upper layer of the volcanic throat and reducing it to shreds. The volcanic ejecta fell and formed large, flat cones (if the explosion was violent), and small, steep cones (if the explosion was weak).

The convective movements of the lava then forced this material to fill the craters; then the inner surfaces of the craters were eroded and widened to form a small lava lake (Illustration 1d).

Successively, the lava overflowed and destroyed an entire crater wall and covered the lava from the main eruption (Illustration 1e). Once consolidated, the lava could be recognized because it lacked the bubbles characteristic of the lava from the preceding eruption; moreover, it could be recognized because it did not cover the entire surrounding area.

The eruption then terminated. Only small quantities of gas and lava were emitted from the central part of the old, partially destroyed crater. The lava flowed over the ground, solidified, and formed cones with steep slopes (Illustration 1f).

of lava and tuff. Thus the Strombolian type of volcanic activity produces composite or stratified volcanoes.

VULCANIAN ERUPTIONS

Vulcano is one of the volcanic Aeolian Islands in Italy. Its eruptive apparatus has given its name to another type of volcanic activity in which the magma is extremely viscous both because of its low temperature and because of its highly siliceous chemical composition. Rising from the reservoir, the magma obstructs the volcanic throat and forms a kind of plug or volcanic stopper. Every resumption of activity is accompanied by violent explosions. Volcanic gases accumulate until the volcanic plug has been pulverized. Consequently, the eruptive force is exhausted in a single explosion. Fluids are rarely emitted, but sometimes great angular blocks of solidified rock are ejected. In a violent explosion, the pulverized materials that are erupted spread over the sides of the volcano. In more moderate phases, these materials are ejected into the cone formed by more violent explosions. The two largest Italian volcanoes, Etna and Vesuvius, have had both Strombolian and Vulcanian eruptions. The structures of these volcanoes reveal where they have been eroded by water or fractured by violent eruptions.

PELÉAN ERUPTIONS

The Peléan-type of eruption, named after Mount Pelée on the West Indian island of Martinique, is characterized by the emission of viscous lava that solidifies so rapidly that it forms a dome. Sometimes lava is expelled in solid form. In the series of volcanic explosions that occurred on Mount Pelée in 1909, the volcano ejected a great lava plug shaped like a giant spine or needle; the top of this spine was raised about 300 m (about 1,000 ft) above the dome. However, the needle-like shaft collapsed in a short time and its fragments fell on the dome. Volcanoes in the Auvergne region of France have also exhibited Peléan-type eruptions in the past. They are characterized by glowing avalanches of incandescent material that may attain speeds up to 169 km (100 mi) an hour.

INITIAL ERUPTIONS

Eruptions that occur after a period of inactivity are called initial eruptions. If they occur following the perforation of an old plug that obstructed the volcanic throat, they are called obstructed conduit eruptions. If they involve the flow of materials from fissures or pipes opened on the slopes of the volcano, they are called lateral eruptions. Sometimes, the covering on the volcano is very thick; then the magma may open a path through the ground surrounding the volcanic landform, thus forming a new volcano. Most of Mount Etna's eruptions occur from lateral vents. Because of the height of the mountain, the lava flows from the sides of the volcano rather than from the central throat.

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PARICUTIN VOLCANO—This Mexican volcano is the most famous example of initial perforation. On February 20, 1943, so much material emerged from a fissure in the ground that it formed a hill about 10 m (about 32 ft) high. However, it continued to grow until it reached a height of 380 m (about 1,200 ft). Today the volcano is completely dormant.

Undoubtedly, the most famous initial eruption was that of Vesuvius, A.D. 79, described by Pliny the Younger in his famous letters to Tacitus. In more recent times, other noteworthy initial eruptions have occurred. For example, in 1883, Krakatau, situated in the Sunda strait between Java and Sumatra, erupted and destroyed two thirds of the island. Violently erupted ashes reached the stratosphere and remained there for several years. After the explosion, a submarine earthquake produced a tidal wave or tsunami that inundated neighboring islands, killing an estimated 36,000 people.

Another example of a violent eruption was that of Conseguina in Nicaragua. The volcano erupted 50 billion m^3 (about 1.75 trillion ft^3) of volcanic materials.

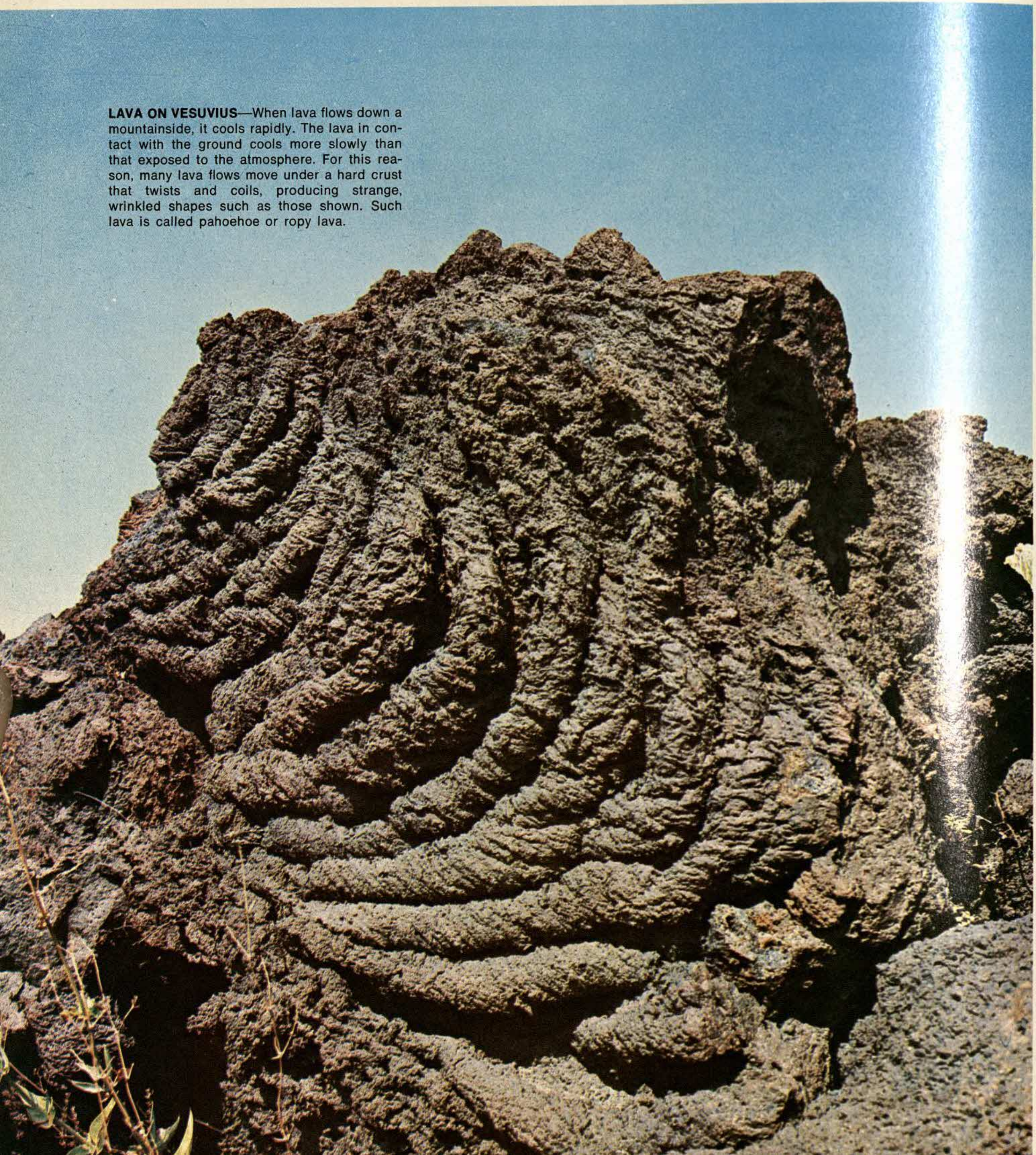
INITIAL PERFORATIONS

An initial perforation differs from an initial eruption in that it does not reopen an obstructed volcanic throat, but creates a new one. The most famous recent instance occurred at Parícutin in Mexico. On the evening of February 20, 1943, a farmer saw a small fissure open in his cornfield; hissing, fetid gas, transporting sand and gravel, issued from the fissure. During the night so much material came out of the crevice that it formed a cone-shaped hill 10 m (about 32 ft) high. However, activity had not ceased, and by the next evening the cone had already grown to a height of 50 m (about 160 ft). Over a four-month period the volcano reached a height of 270 m (about 880 ft); lava flows from the foot of the volcano continued to spread, completely destroying the town of Parícutin. The volcano, which eventually reached a height of 380 m (about 1,200 ft), has been dormant since 1952.

Other examples of initial perforation include Monte Nuovo in the Phlegrean Fields (Naples) and Arso on the island of Ischia. An unusual perforation took place in Sumatra, producing 1,000 billion m^3 (about 35 trillion ft^3) of pumice and other unconsolidated materials and the subsequent collapse of the roof of the magma chamber containing them. This formed a depression that filled with water and became a lake (Lake Toba) about 100 km (about 62 mi) long and about 30 km (about 19 mi) wide.

PRODUCTS OF VOLCANIC ERUPTIONS

lava and pyroclastic materials



LAVA ON VESUVIUS—When lava flows down a mountainside, it cools rapidly. The lava in contact with the ground cools more slowly than that exposed to the atmosphere. For this reason, many lava flows move under a hard crust that twists and coils, producing strange, wrinkled shapes such as those shown. Such lava is called pahoehoe or ropy lava.

Volcanoes expel different kinds of materials with various chemical compositions and states of aggregation. Among these materials are gases, solids, fluids, and dust. This discussion is concerned with the origins of these products and their deposition around volcanoes.

VOLCANIC EJECTA

When magma rises in the volcanic conduit or throat, it is usually driven up by gases escaping from the magma itself. It has been estimated, for example, that the lava emerging from the main conduit of Mount Etna is forced upward when its gas pressure reaches about 1,000 kg/cm^2 (about 342 lb/in.^{2}). The gases that escape from a volcanic vent drive up rock fragments, moving them forward in the same way as the wind blows objects that offer resistance. The conduit where this occurs may be tens or even hundreds of meters long.

Volcanic ejecta can travel at extremely high velocities. During the famous eruption of Krakatau (a volcano in the Sunda strait between Java and Sumatra) in 1883, several heavy masses were hurled to a distance of 20 km (about 12.5 mi); lighter masses were found up to 40 km (about 25 mi) away.

Solid fragments hurled to a distance are generically called volcanic ejecta; they have different names according to their characteristics. For example, the smallest ones, measuring a few centimeters across, are called cinders or lapilli, which means "small stones." These do not land far from the volcanic vent because, although their initial velocity is great, they are quickly slowed by friction with the air.

VOLCANIC BOMBS

Often the gases rising in the volcanic conduit draw up lava fragments. As these fragments congeal rapidly in the air, they become rounded; for this reason they are called volcanic bombs.

Sometimes a bomb solidifies as it rises through the conduit, and the gases that propel it are still under high pressure. If this happens, the bomb becomes a hollow stone filled with gas under high pressure. Contact with the ground or rapid cooling can fracture it, causing it to explode; it is then called an explosive bomb.

Volcanic ejecta do not always have the same composition as the lava erupted. Often, in fact, the ejecta are rock fragments that were a part of the rock that had been penetrated by the magma conduit; these fragments were torn away by the rapid flow of magma.

PUMICE AND VOLCANIC GLASS

Sometimes a piece of lava is expelled from the volcanic conduit while it is solidifying. The gases in it escape in the form of bubbles and cause considerable dilation. Such volcanic ejecta resemble sponges and are called pumice. Pumice is often so light that it can float on water.

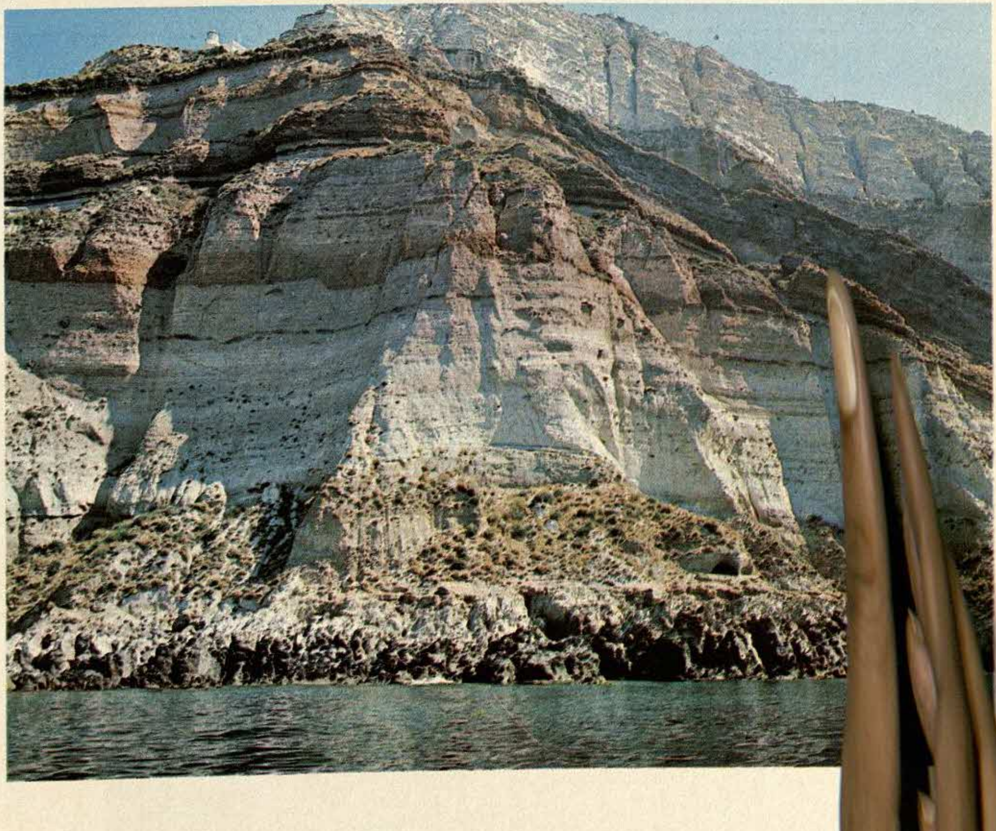
Solidified lava is a very refractory material; that is, it is not a good conductor of heat and thus can be used as an insulator. Lava swollen by numerous gas bubbles has even greater insulating properties. In fact, heat can only be conducted through the thin cell walls of the spongy mass or through the gas contained in the cells. For this reason, pumice is widely used in the building industry. Ground into a coarse powder, it is an ingredient of heat-insulating panels used in the walls of houses.

Some lava solidifies to form glassy rather than granular rocks. Obsidian is one such volcanic rock. In Italy, enormous masses of obsidian are found in the Lipari Islands. The material was used for utensils by the prehistoric inhabitants of southern Italy; obsidian can be worked with the same chipping technique as that used to make flint utensils.

LAVA

In the crystallization of a substance, the size of the crystals is determined largely by the speed with which the substance cools—usually, the slower the cooling process, the larger the crystals. Magma that is erupted as lava cools much more quickly than magma deep in the Earth, and consequently has a different crystalline structure. Experts in mineralogy and petrography can identify the condi-

TUFF—A striking example of tuff layers can be seen on the island of Ischia, where Epomeo, a now dormant volcano, once erupted great quantities of dust. With the passage of time, very thick banks of tuff were formed on many parts of the island. Their structure has been revealed by erosion.



VOLCANIC BOMBS — Sometimes volcanoes erupt lava fragments that coalesce and roll against the walls and become rounded as they cool; such ejecta are called bombs. If they solidify before being expelled from the conduit, they can even explode because they contain gas under high pressure.

tions under which a rock has been formed by observing the characteristics of its mineral crystals.

The heights of Vesuvius and Mount Etna are characterized by recent, black lava flows that resemble enormous, dark, swollen rivers flowing down the slopes of these volcanoes. Sometimes vegetation begins to take root at the edges of the lava. At first this occurs with great difficulty because lava is extremely compact; eventually, the roots of the plants that grew first split the rock and prepare humus for luxuriant vegetation. The composition of lava is very similar to the average composition of the lithosphere, and it also contains many rare elements that favor the growth of plants.

If lava flows from submarine volcanic vents, the gases that escape either condense immediately because of the extremely high pressure on the ocean floor —or else they do not escape from the magma mass. In the latter case, the lava spreads quietly, as occurs in the injection of a sill. Because lava is not a good conductor of heat, it spreads underwater without solidifying entirely. A solid, superficial crust (a few meters thick) in contact with the water is sufficient to permit the underlying lava masses to remain fluid for a long time.

Lava has at times been deposited on the surface of a glacier, and occasionally hot lava has even been covered by ice. Alternating layers of lava and ice occur only with the melting of a thin layer of ice and the consolidation of a thin layer of lava.

TUFFS

The dust emitted by a volcano falls around the landform and is deposited on the ground or on the floors of oceans or lakes. At first, the dust is loose and soft, like ash; with the passage of time and particularly the action of the water, the dust particles cohere and form a rock called tuff. Tuff, which is weak and easily worked, often has a color varying from light ocher to dark brown. The Roman catacombs are simply tunnels excavated in tuff produced by volcanic activity in the Latium region of Italy. Sometimes volcanic dust falls into the sea and mingles with sediments, forming underwater tuff.

GLOWING CLOUDS AND AVALANCHES

In Strombolian- and Vulcanian-type explosions, the volcanic vent emits only one mass of gas containing minute particles of dust. Such hot gases are called *nuées ardentes* (glowing clouds). Rushing down the flanks of a volcano, the clouds burn everything in their path. Sometimes their action is so violent that they drag along large masses of rock, in which case they are called glowing avalanches.

LARGE-SCALE VOLCANIC ERUPTIONS

some historic highlights

Active volcanoes display their vitality by continuous or intermittent emissions of gas, dust, and lava. This continuous, lesser activity is reassuring to the people who live in the vicinity of active volcanoes. It indicates that the gases, which escape during the cooling of the underlying pluton, are not accumulating pressure and that a catastrophe is, therefore, not imminent because the volcanoes are gradually letting off the "steam" that escapes from the magma.

On the other hand, a dormant volcano is a dangerous unknown quantity. The dormancy of the volcano may be due to the fact that the magma in its reservoir has cooled, reaching the hydrothermal stage; or it may be due to the fact that the conduit or throat of the volcano has been obstructed, in which case pressure is building up internally. In the latter case, of course, the possibility of a disastrous resumption of activity exists.

THE PLINIAN ERUPTION OF VESUVIUS

During the entire period of the development of Roman civilization, Vesuvius exhibited no appreciable signs of activity. Nonetheless, in A.D. 63 the area surrounding the mountain was shaken by a succession of increasingly violent earthquakes.

On August 27, A.D. 79, the eruption that destroyed Pompeii, Herculaneum, and Stabiae occurred. Its violence shattered much of the circular wall of Mount Somma, the ancient crater of the volcano that had been active in prehistoric times. The eruption caused the death of tens of thousands of people, including Pliny the Elder, the Roman natural historian. The observations recorded by his nephew, Pliny the Younger, together with the uncovering of the buried cities of Pompeii and Herculaneum during the last century, permit a reconstruction of the catastrophe.

At first, ashes were deposited on the streets and rooftops of Pompeii without causing great damage. However, the suffocating, poisonous fumes escaping from the fallen ashes and the high temperature of the air persuaded many people to leave Pompeii. Soon afterward, the accumulated ashes began to set fire to houses, to make roofs collapse, and to render the streets impassable. A thick layer of ashes accumulated on the dead city, carbonizing all the organic substances they covered. In this way, the bodies of those who remained in Pompeii were consumed by the heat. Cavities that reproduced their shapes in detail remained in the hardened ashes. In addition, the column of red-hot gases that rose into the sky during one of the eruptions also drew up a great quantity of water vapor that cooled on rising and

THE TRAGEDY OF POMPEII—This replica (Illustration 1a) of an inhabitant of Pompeii was made from a cavity left in the hardened ashes. The man makes a desperate gesture in attempting to protect himself from the shower of ashes and lapilli that fell on Pompeii A.D. 79. He hides his face in his hands, almost as though he were trying to ward off the sight of relentlessly approaching death. The shrinking position of the dog (Illustration 1b) also demonstrates the tragedy that can accompany massive volcanic eruptions.

1a

1b

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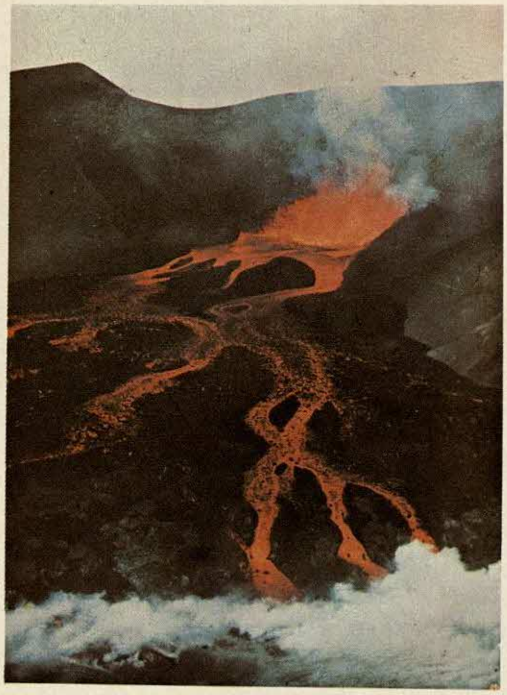
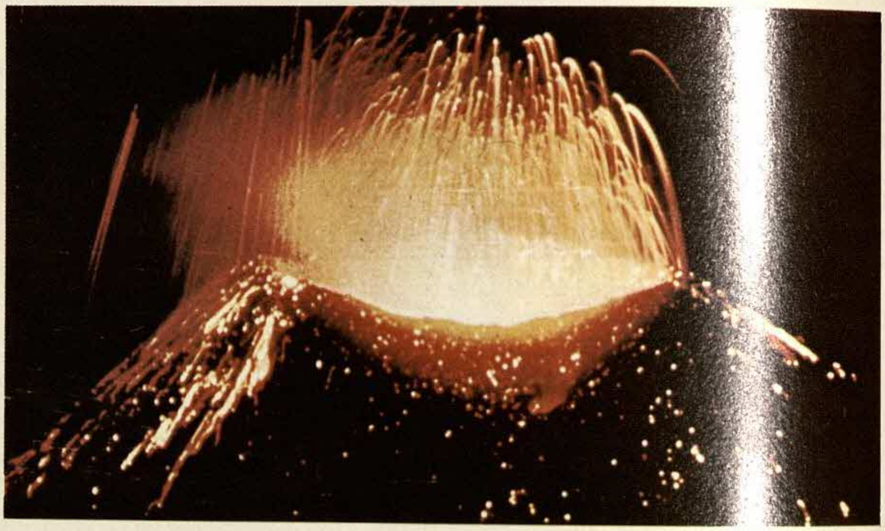


ICELAND—This photograph shows Surtsey volcano in full activity. This particular volcano is very young, having risen from the sea off the coast of Iceland on November 14, 1963. This is not an unusual phenomenon; in fact, all of Iceland is a vast volcanic plateau composed of innumerable layers of lava.

MOUNT ETNA—A phantasmagoria of lights in the night, a cloud of reddish smoke in the sky: such is Mount Etna in eruption. This, the largest Italian volcano, has been active for thousands of years. Eruptions from more than 200 subsidiary cones have shaped it into a dome rather than a cone. Up to the halfway mark, the slopes of Mount Etna are dotted with towns, some of which have been destroyed and then reconstructed several times.

3



produced precipitation. The rains fell on the side of Vesuvius facing the sea, that is, the side toward Herculaneum and Stabiae. They saturated the freshly fallen ashes and dust and transformed them into a fluid mud that hurled itself down the mountainside, burying the two cities.

THE ERUPTION OF MOUNT PELÉE

On the island of Martinique, the town of St. Pierre was dominated by Mount Pelée, a volcano 1,300 meters (about 4,200 ft) high. After a few days of warning signals, at 7:45 on the morning of May 8, 1902, the flank of the volcano was rent by an explosion. It produced a *nuée ardente* or glowing cloud that thundered down on St. Pierre, destroying the town and its inhabitants. The only survivor was a condemned murderer who was protected from the great heat by the thick walls of his cell. He was discovered two days later, terrorized but still alive.

The glowing cloud proceeded on its march to the sea, burning all the ships anchored in the harbor. After having lost half its crew, only one English ship, a burned-out hulk, remained afloat. The phenomenon was observed by people aboard other ships off the coast. In fact, these ships themselves suffered casualties and damages. The sea boiled at the point where the glowing cloud touched it, and hot steam was added to the avalanche of gas and dust. The smokestacks and masts of one of the surviving ships were torn away by the hot blast.

THE DANGER OF QUIET ERUPTIONS

The lava exuded by volcanoes that erupt quietly is usually fluid; it can be even more dangerous than viscous lava. Viscous lava flows slowly; although it destroys everything in its path, at least it allows some chance of escape. In contrast, fluid lava flows with great speed; it may rush down river valleys, spreading devastation everywhere.

When the lava flow reaches the sea, it can construct a promontory. In a successive lava flow another promontory may be formed, separated from the preceding one by a cove. A subsequent lava flow may descend on the area between the two promontories, destroying the cove.

THE LAKI FISSURE ERUPTION

In Iceland, in 1783, a fissure about 16 km (about 10 mi) long opened up; in a short time 15 billion m^3 (about 530 billion ft^3) of lava poured out. The lava flows lasted for about two years, covering a vast area measuring 500 km^2 (about 190 mi^2). The enormous accumulation of lava produced by this eruption disturbed the entire mountain region; it caused landslides, floods, and invasions of ice and mud. The eruption killed 230,000 head of cattle and 9,000 inhabitants of the area.

KRAKATAU

Impressive eruptions have occurred in relatively uninhabited areas without causing great loss of life and property. The massive eruption of Krakatau in 1883 serves as a classic example. This eruption was not without its casualties, however. The cataclysmic explosions that destroyed this volcano generated enormous tidal waves that inundated nearby islands, killing thousands of people.

Nevertheless, it is easy to imagine how

much devastation the eruption might have caused if the volcano had been located near a large city instead of on a small, almost uninhabited island. In fact, the Krakatau catastrophe left a 300-m (about 1,000 ft) depression in the ocean floor where a volcanic peak 800 m (about 2,600 ft) high had stood. The rest of the mountain was pulverized; the extremely fine dust reached the upper stratosphere and circled the Earth several times. The dust fell back to Earth for several years, and for a considerable length of time the intensity of solar radiation was reduced by about 20 percent all over the world.

FORECASTING ERUPTIONS

The primary causes of earthquakes and volcanic phenomena lie in the interior of the Earth. In the case of eruptions, the study of a volcano's behavior can furnish useful data for forecasting its activity. It has often been observed that volcanoes have a cycle of activity, alternating between active and dormant periods on a fairly regular schedule. For example, Hawaiian volcanoes have a cycle of about ten years. Some experts have tried to connect the cycle with sunspots, but it seems that their hypothesis is not valid. Other volcanoes (Vesuvius, for example) have less regular cycles, with phases that vary from decades to centuries.

The mechanism of volcanic eruptions explains the periodicity of eruptions. Each eruption, particularly if it is violent, produces a partial emptying of the magma chamber. When the internal pressure of the magma is not sufficient to force it out of the conduit or throat, the magma withdraws because the gas that expanded it and forced it upward has escaped. For magma to return under pressure, a sufficient quantity of gas must escape from its mass; this inevitably occurs as long as the magma has enough time to cool.

The factors underlying the cyclic behavior of a volcano's activity also serve to explain the warning signals of an eruption: greater emission of volcanic vapors, change in the course of springs on the volcanic mountain, local increase in ground temperature, and increase in earthquake activity.

Earth satellites with infrared sensing devices soon will increase the data on temperature changes at volcanoes, hot springs, and steaming vents. Another forecasting factor associated with active volcanoes consists of the many small and distinctive earthquakes that are apparently related to the underground movements of molten rock. Volcanic tremor, a vibration that can be recorded only on sensitive seismographs near active volcanoes, sounds like a humming of the ground. Geophysical investigations of changes in the magnetic, electrical, and gravity fields near active volcanoes are still largely in the theoretical or early experimental stages, but they hold much promise as forecasting factors.

LAVA FLOW — Like a twisting, incandescent river, lava flows down the slopes of Mount Etna toward the valley, leaving destruction in its wake.

VOLCANIC ZONES | the distribution of volcanoes

A cursory study of volcanic phenomena might lead to the belief that volcanoes are spread in random fashion across the face of the Earth. The student might observe that, although volcanoes appear to be more numerous in certain areas than in others, they generally can be observed either isolated or in small groups, either close to or distant from coastlines or mountain chains, either within continents or in the middle of an ocean. However, the distribution of volcanoes is not random; they are located in definite zones with well-defined geological characteristics. These facts provide an explanation of the prime causes of their appearance.

A map is indispensable to a study of volcano distribution. Such a map (Illustration 1) shows all the volcanic zones on the Earth, as well as the most important mountainous regions. Also important to a study of volcanic phenomena is a knowledge of the average chemical composition of the erupted lavas.

THE STUDY OF VOLCANIC ZONES

The regions characterized by the most intense volcanic phenomena are regions near the great folds in the Earth's crust, as indicated in Illustration 1. The shaded areas on the map correspond to the most intensely volcanic zones. They include not only currently active volcanoes, but also volcanoes that were active during the last part of the Tertiary period and the first part of the Quaternary period. In other words, the map covers a span of time dating back some millions of years, during which the most intense orogenic phenomena began—phenomena that led to the formation of high, massive mountain chains such as the Alps and the Himalayas.

It is very interesting to note the so-called "ring of fire"—that is, the great belt of volcanoes encircling the entire Pacific Ocean. With hardly a break, this belt extends northward from Tierra del Fuego through the whole cordillera of the Andes and the Rocky Mountains, and continues through Alaska and the Aleutians in the north. It then extends southward down the western coast of the Pacific Ocean, following through all the islands bordering it, beginning with Kamchatka and passing through Japan and the Philippines as far as New Guinea and the Polynesian archipelago. The ring then continues southward into the Antarctic.

A second important volcanic zone includes the islands that follow the north-south axis of the submerged mountain chain known as the Atlantic Ridge: Iceland, the Azores, the Canaries, Madeira, Cape Verde, St. Helena, and Tristan da Cunha.

Another important volcanic region is that of Europe and Asia Minor. This region extends from the Italian volcanoes of the Mediterranean (Stromboli, Vesuvius, Etna) as far as Anatolia, Arabia, Iran, and the Deccan region in India.

In southeast Asia, a well-defined alignment of volcanoes exists along the Sunda Sea, stretching from Indochina as far as New Guinea and passing through the islands of Sumatra and Java.

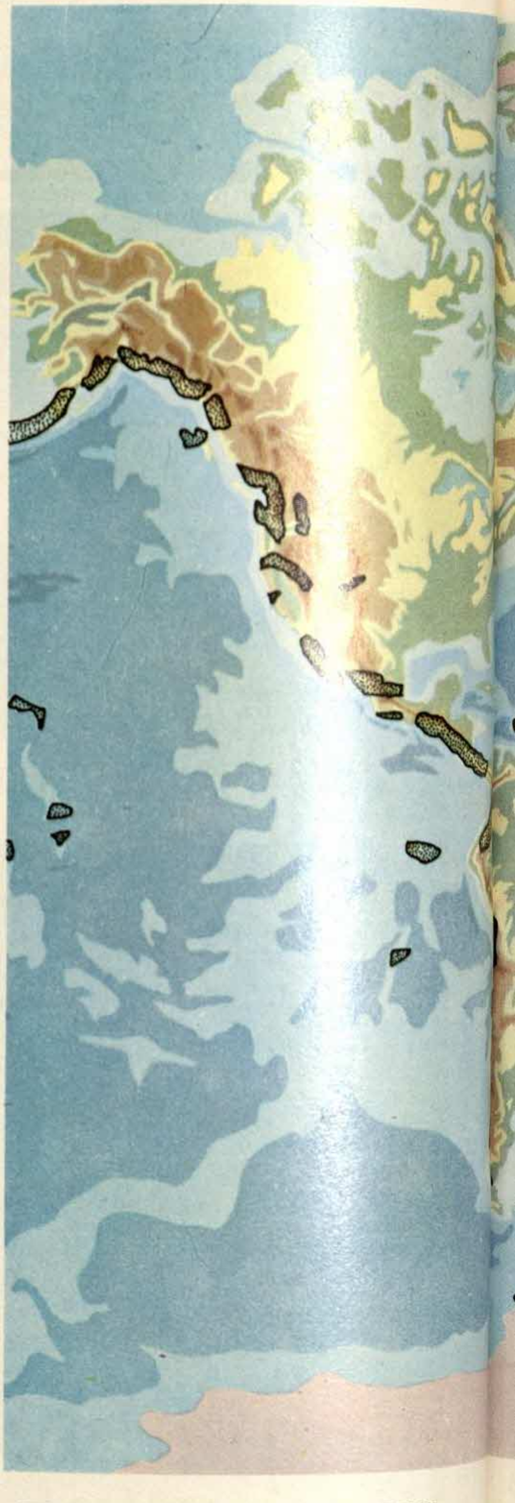
The Hawaiian-Islands alignment in the central Pacific forms a system partially isolated from the "ring of fire" and from the other aforementioned zones.

THE ASSOCIATION OF VOLCANOES WITH TECTONIC PHENOMENA

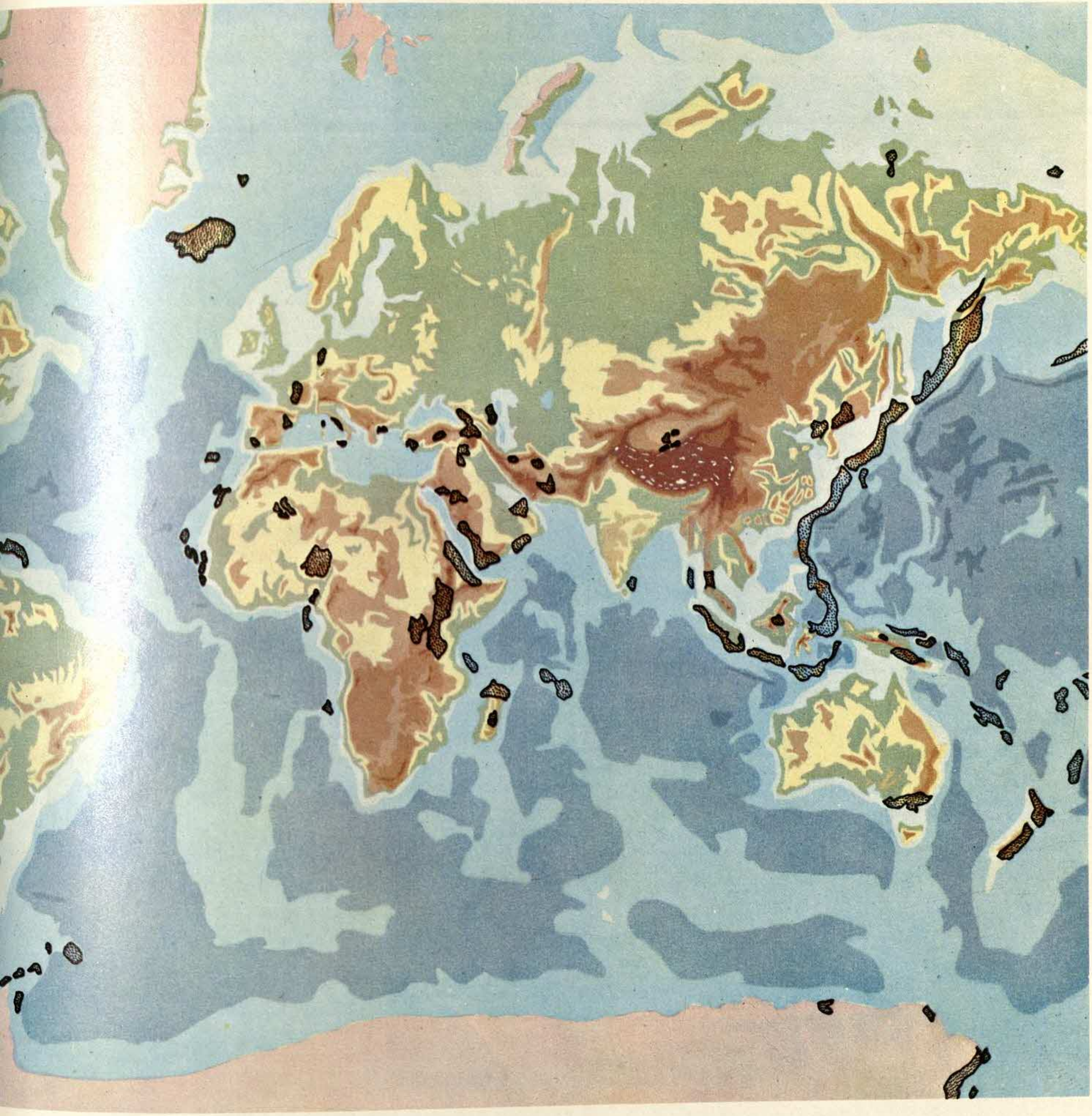
The map in Illustration 1 shows that groups of volcanoes are generally arranged near and parallel to some recently emerged mountain chain, or—in the majority of cases—a mountain chain that is still in the process of emerging. This fact is particularly clear, for example, for that part of the "ring of fire" that follows the western coasts of North and South America.

Sometimes, however, volcanoes are located parallel to a mountain chain and at some distance from it, as in the case of the group that extends from the Mediterranean to Asia Minor. This group runs parallel to the folds of the Alpine, Anatolian, and Himalayan chains, although not exactly along the same axis. The volcanic zones of the Far East, the Sunda Sea, and the Atlantic Ridge also run parallel to great folds.

The group of volcanoes in East Africa forms a special case. In fact, this volcanic line runs parallel to a great tectonic trough located in East Africa and marking its eastern boundary. This fact makes it clear that the elongated vol-



THE DISTRIBUTION OF VOLCANIC AREAS— This map includes the zones where volcanoes are currently active or where they have been active since the end of the Tertiary period. It

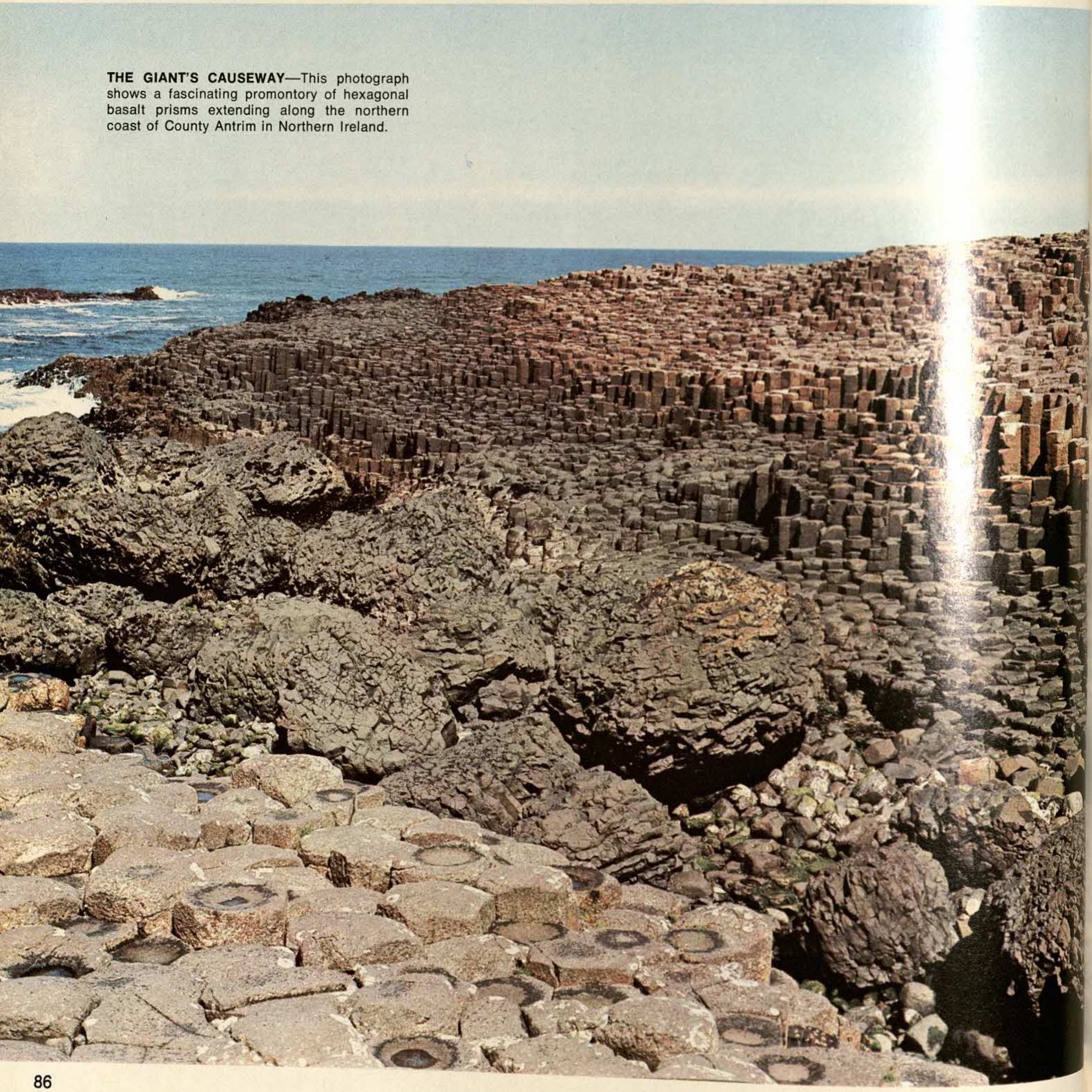


shows that volcanoes are arranged in groups or lines, as, for example, the "ring of fire," which includes all the coasts facing the Pacific Ocean. Closer examination of the map reveals that the volcanic areas are all connected either with areas of intense orogenesis or with large fractures that originated with the folding or sinking of the Earth's crust. Volcanoes are not located precisely along the axis of a great mountain chain; they usually are found parallel to such an axis.

canic zones run parallel to the great folds and are located where horizontal orogenic forces have produced great fractures in the Earth's crust, thus opening the way for the underlying magma.

Orogenic forces were not the only causes of fractures capable of bringing the deep magma to the surface. In fact, the fractures caused by the sinking of the East African tectonic trough had the same effect. (Volcanism has been endemic in Africa throughout geologic time.) Many of these fractures may be observed on the surface, but not all of them have gone deep enough to enable the volcanic magma to rise to the surface.

Finally, it is important to note that, frequently, no volcanic phenomena exist along the axes of the great orogenic ridges. This can be explained by noting that sometimes it is difficult for the magma to find a path leading to the surface. In such instances, plutonic rocks may possibly be formed. In fact, a map showing the location of the major plutonic deposits in the world indicates that they are to be found along the lines where the mountain chains have been wrinkled most and lifted highest. Volcanoes are also formed where the lifting of the mountain chains is most intense, but they are more often found alongside them.



THE GIANT'S CAUSEWAY—This photograph shows a fascinating promontory of hexagonal basalt prisms extending along the northern coast of County Antrim in Northern Ireland.

ROCK DEFORMATION | distorting forces

Plutonic forces were primarily responsible for the early evolution of the Earth's surface. In the lithosphere, about 95 percent of all rocks were formed by the solidification of magma. These rocks are igneous; that is, derived from the solidification of lava that was originally fluid because of residual terrestrial heat or heat produced by radioactive substances in the lithosphere. Movements caused by deep shifts of the matter forming the Earth's mantle resulted in the phenomenon of orogenesis—the appearance of the great mountain chains.

Rock deformation is one of the results of great and small movements of the Earth's crust. The history of the geological movements that a region has undergone can be traced by a study of the rocks in that particular region. The development of life in the region can also be located and interpreted. In addition, a study of the rock folds of the Earth's crust serves as a basis for exploration of the buried strata. Rocks are permanent and faithful witnesses to the events of millions of years.

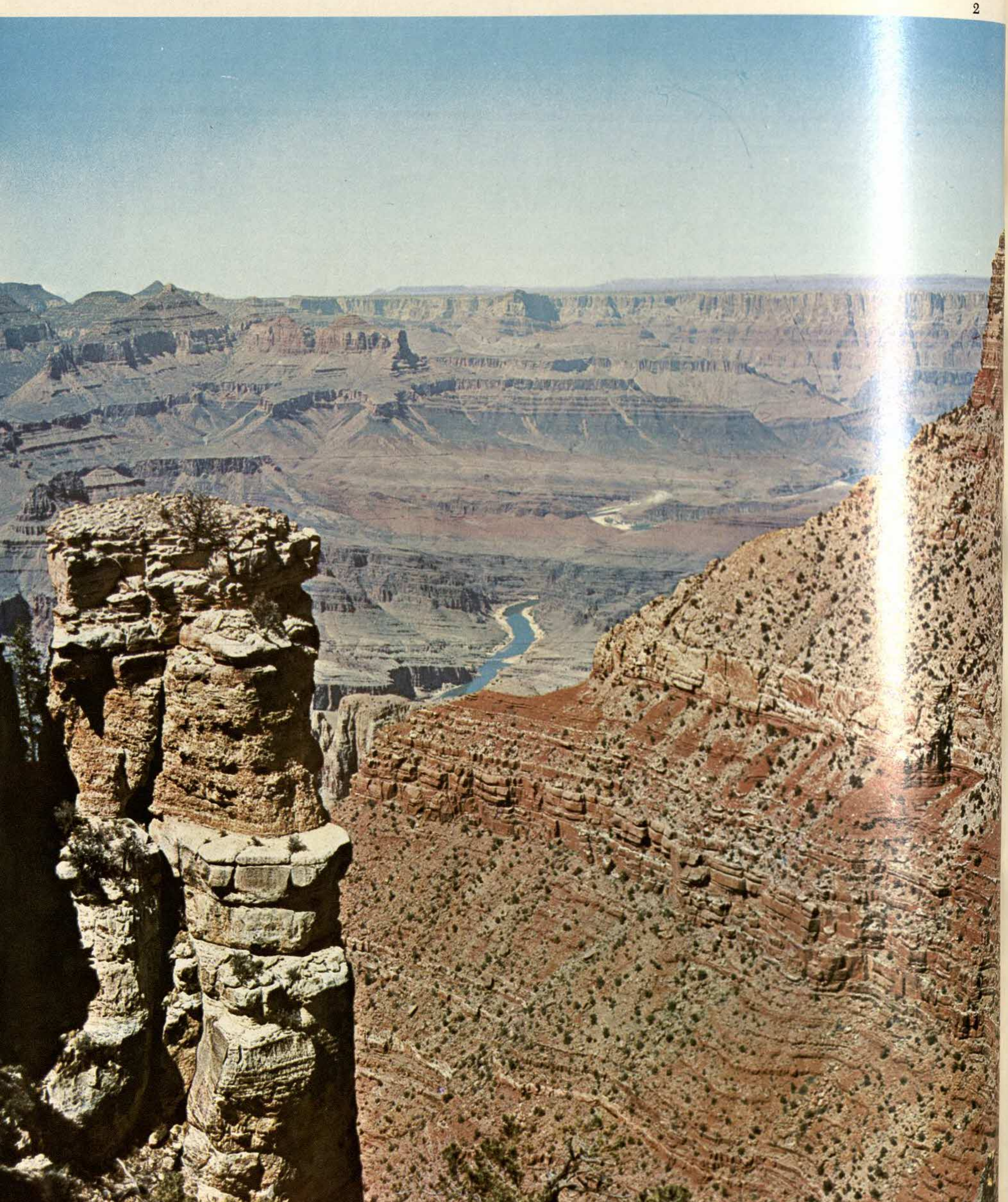
IGNEOUS ROCKS AND SEDIMENTARY ROCKS

Igneous rocks, produced by the solidification of magma, often seem to be made up of crystalline grains less than a few millimeters in size, arranged irregularly within the rock but giving a homogeneous appearance. Sedimentary rocks are formed of eroded rock particles that are carried to the sea by rivers and deposited on the seabed. These rocks are often composed of parallel strata that can be distinguished from one another by slight differences of color, compactness, size of the crystals, and sometimes chemical composition. Strata of sedimentary rocks indicate whether, since their formation, they have been altered or bent by forces exerted in the Earth's crust. Sometimes sedimentary rock strata retain the parallel configuration they had before they were lifted up from the seabed where they were formed, but this is rare. Most such rocks have been deformed, and this is immediately apparent.

Metamorphic rocks, too, may display deformations produced by forces acting on them. These rocks are sometimes of igneous origin, sometimes of sedimentary; they have been greatly transformed by pressure and by heat resulting from this pressure. The crystals are often deformed, in some cases even flattened, and in other cases completely recrystallized because of the great pressures exerted on them. Despite their different origin, metamorphic rocks, which look much like the sedimentary rocks, preserve the history of the forces to which they have been subjected.

FOLDS — The chaotic position of these rocks reflects the potent forces present within the Earth.

SEDIMENTARY ROCKS—The Grand Canyon in Arizona best typifies the desolate and imposing appearance of a vast area made up of sedimentary rock strata.



THE FLEXIBILITY OF ROCKS

Sedimentary rock strata are often found in which the strata have been subjected to such strong forces that they have been tipped up to a sharp incline—yet they have undergone this considerable bending without being shattered.

When subjected to extreme forces, almost all solid matter may undergo plastic deformation—as, for example, a piece of wire when it is bent. However, if a body is subjected to excessive pressures, it breaks; its limit of plasticity has been exceeded. The mechanical properties of rocks can be observed, but the proper equipment and skill are required. A fine splinter of rock is easily broken between two fingers; the forces exerted on it have exceeded its limit of plasticity. However, if the splinter is subjected to only fairly light pressure, it is difficult to detect its plastic deformation—that is, whatever disappears when the pressure ceases. The plastic deformation of a rock can only be observed with the proper equipment, plus one other item that is practically impossible to find in even the most modern and best-equipped laboratories: an extraordinarily long time.

The plasticity of rocks becomes apparent only over a very long period, thousands and thousands of years. Moreover, it may originate in many ways. Principal among these are heat and recrystallization.

HOW ROCK IS DEFORMED

Heat may cause a high degree of plasticity in rock so that, at high temperatures, the atoms forming the crystals partially lose their structure. Thus, the crystal loses its true structure (Illustration 4a) and takes a form similar in many ways to that of glass (Illustration 4b), in which the atoms of the component substances are arranged irregularly. Under these conditions, prolonged pressures cause a slow movement of the atoms from one point in the crystal to another, and the crystal itself is gradually deformed. In broad terms, the process is analogous to the heating of metals to make them more malleable. At high temperatures their crystalline network loses its regular structure and the atoms move about to form a new crystal whose outlines change to follow the direction of the forces acting on it. This process takes a great deal of time, but in the geological history of the lithosphere there has been no shortage of that.

Recrystallization under pressure in the presence of a liquid can also cause plastic deformation of rocks. A rock may seem impermeable at first sight; however, if a hole is drilled into its surface and water poured into the hole, the water filters away—very slowly. Excepting vitreous rocks, which are virtually impermeable, even fairly compact rocks are slightly porous. Water impregnating the subsoil filters through, generally around the outlines of the crystalline grains of which a rock is formed. When a rock impregnated with water is subjected to extremely heavy pressure—many tons per square centimeter—deformation takes place (Illustration 5). Such deformation is one of the more subtle variations.

FOLDS

The most interesting rock deformation is the simple fold. This bending process is best seen when it has occurred in sedimentary rocks, since their structure naturally shows it. Observation and study of rock folds reveal the force of the movements that the Earth's crust has undergone. The Earth is not stable, and few points have escaped this bending process. The bending process is constantly taking place. The curvature may amount to only a few millimeters a year, a few thousandths of a millimeter a day, but the millimeters add up to meters in a thousand years and to kilometers in a million years—a short span in the history of the Earth.

DEFORMATION—The rocks shown here are sedimentary; the strata lie at a steep angle to their original position. The angle is a result of forces in the Earth's crust.

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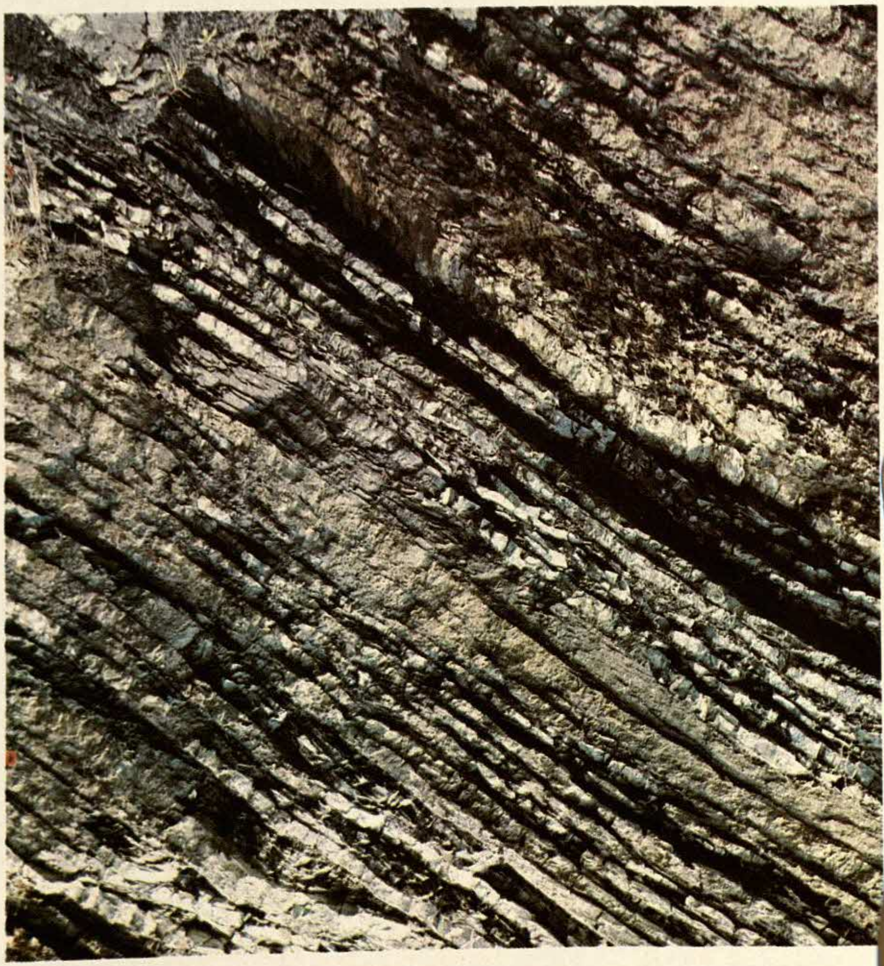

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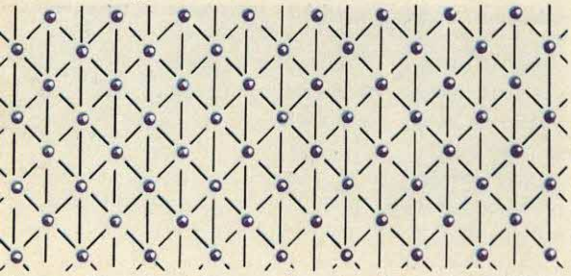

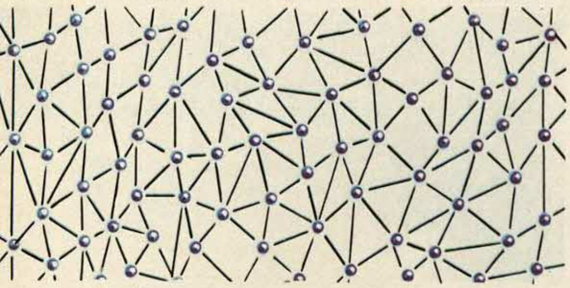

4b

CRYSTALLINE AND VITREOUS STRUCTURE —Heat may render rock extremely malleable. At high temperatures, a crystal loses its perfectly regular form (Illustration 4a) and becomes irregular (Illustration 4b). The result is deformation of the rock.

THE DISTORTION OF ROCKS—If a solid is placed in a liquid and the two are compressed, the solubility of the solid is increased. The substances of which rock is formed are not highly soluble in water. Geologically speaking, however, even quartz, which is less soluble than glass, is a soluble substance, especially if the water temperature is fairly high. The illustration shows how the crystal-water composition of a rock, under heavy pressure in the direction indicated by the arrows, is greatly compressed. At the point of contact **a** between crystals, the atoms tend to pass into solution. At point **b,** however, the same solution, which has become saturated, is subjected to far less pressure. At this point, the atoms tend to leave the solution and attach themselves to the first crystal they find. After a time the crystal itself is distorted, flattening out horizontally to the faces where pressure was exerted.

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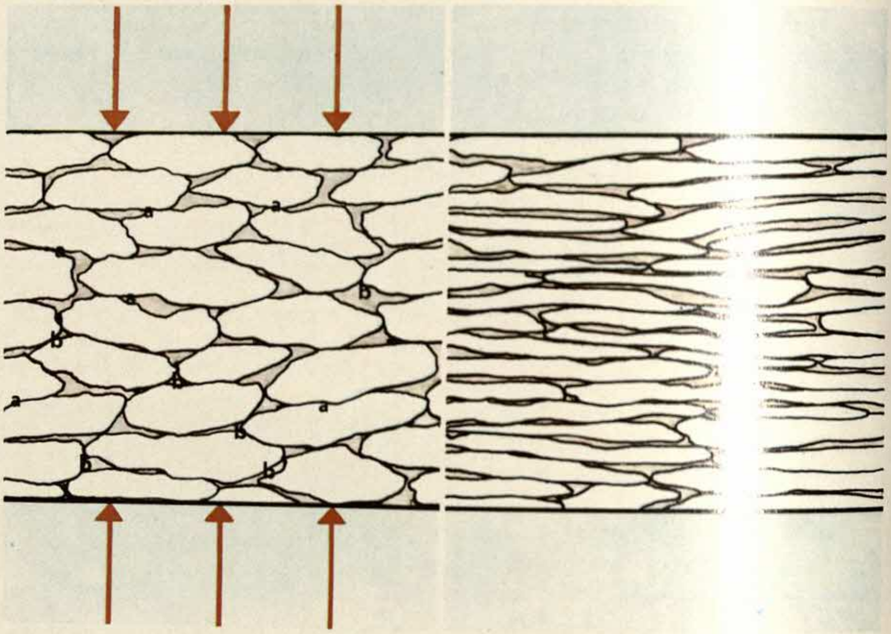


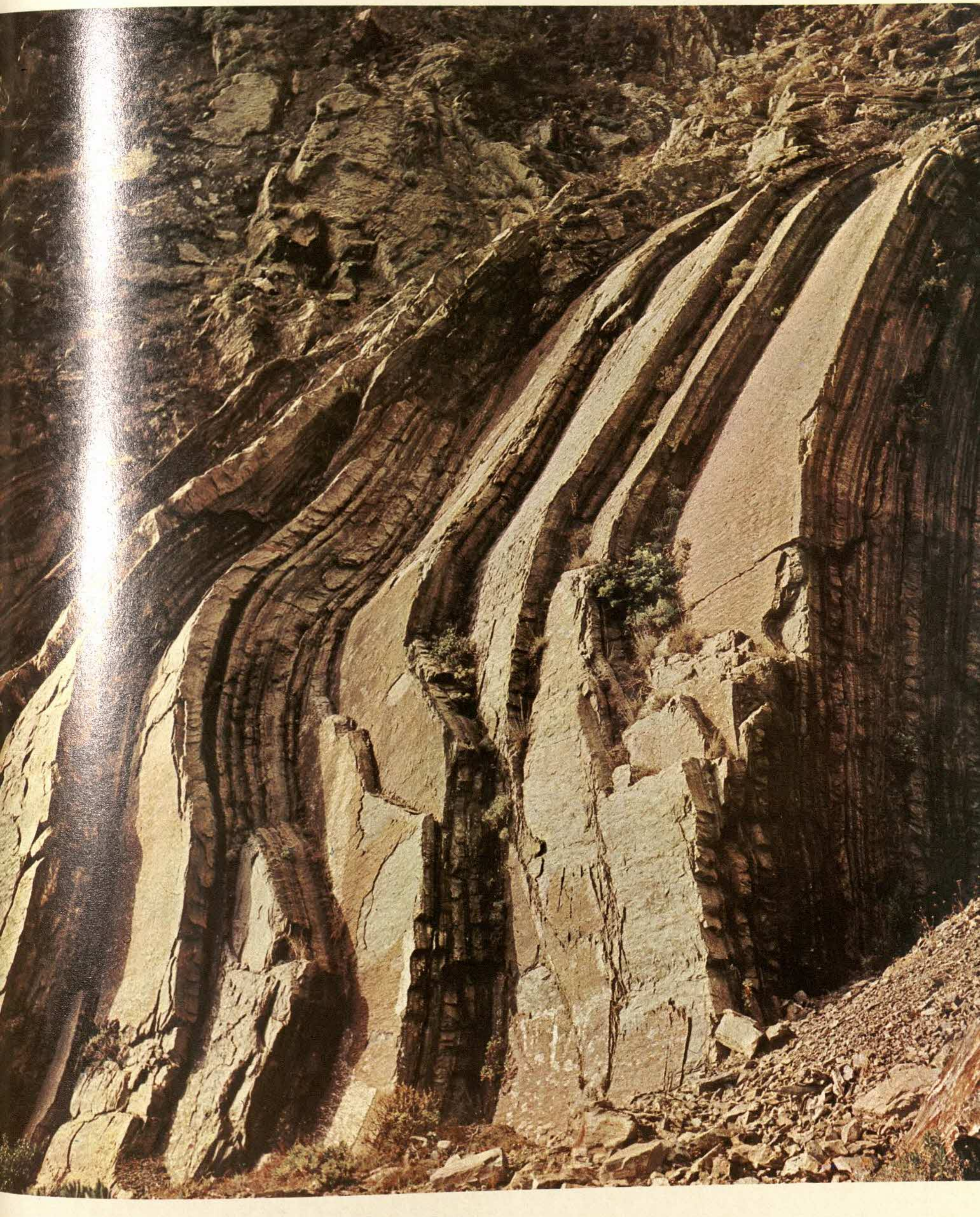
EXAMPLES OF CRUSTAL MOVEMENTS

Abrupt and large-scale displacements of bedrock have taken place within historic time. Part of the Alaskan coast was raised instantaneously as much as 47 ft (14.5 m) in 1899. Not surprisingly, the movement was accompanied by a major earthquake. Other extensive breaks in bedrock that coincided with earthquakes have been recorded in Chile, California, Japan, Italy, and other countries. Slow movements affecting wide areas are revealed in evidence both historic and older. Marks that were made at high-tide level along the Norwegian coast more than a century ago are now several feet above the reach of tides. Evidence of broad uplift is also conspicuous in Newfoundland and in other parts of Canada. Such a movement, involving the gradual bending of a wide surface, is known as crustal warping. In addition to warps, other structural features that record deformation include folds, faults, joints, and cleavage.

In major mountain chains, folding has affected belts that are tens of miles wide and hundreds of miles long. Folding can occur only in layered rocks, and it is best developed in thick sections of sedimentary beds.

Faults are great breaks in bedrock along which displacement occurred parallel to the fracture. Dimensions of faults range from inches to hundreds of miles. Sudden slips on active faults cause earthquakes. Joints are breaks along which no perceptible movement has occurred. They are present in nearly all large exposures of bedrock. In igneous rocks, many joints have formed by contraction upon cooling. Joints that cut rocks of all kinds probably resulted from various kinds of deformation. Cleavage has been developed in many large masses of rock under high compressive stress. In almost all mountain belts, shale in closely folded beds has been transformed into slate. Cleavage, cutting across the original bedding, divides the slate into extremely thin plates that have remarkably plane surfaces.

CLASSIFICATION OF FOLDS | wavelike rock formations



ROCK STRATA—These rocks on Italy's Ligurian Riviera are arranged in well-defined and folded strata (Illustration 1).

If a cardboard box were filled with layers of different-colored modeling clay and the sides of the box were then crushed in from all directions, the mass of the clay would be pushed up in the center, with the different layers partially intermixed. This situation is similar to the way in which the rocks in the lithosphere have been distorted through time—as have those in the deeper zones of the terrestrial crust—the zones that cannot be directly studied.

Because they were formed in many different ways, the folds in the Earth's crust have assumed a wide range of shapes. The following illustrations describe the principal types of folds and explore the relationships between the folds in rock strata and mountain contours. Folded strata are characteristic of many of the world's mountain ranges.

THE MONOCLINAL FOLD—This simplest type of fold is caused by the lifting or sinking of part of a complex of rock strata. The strata remain horizontal at the ends of the fold. The fold has two "elbows," one convex **a** and the other concave **b.** The first is called the upper elbow; the second is the lower elbow. The connecting slope between the two elbows is called a limb. The arrows show the directions in which the forces responsible for the formation of the fold were exerted. This type of fold is very common, especially in areas where the orogenic forces that caused the buckling were not very intense.

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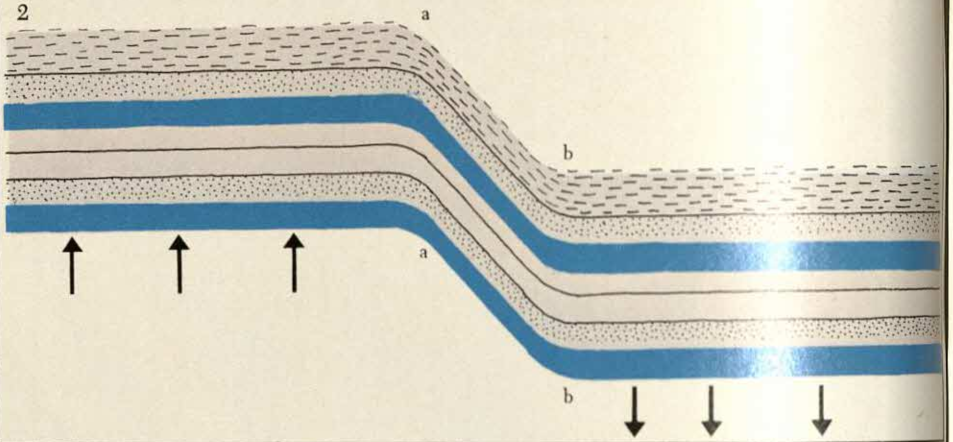
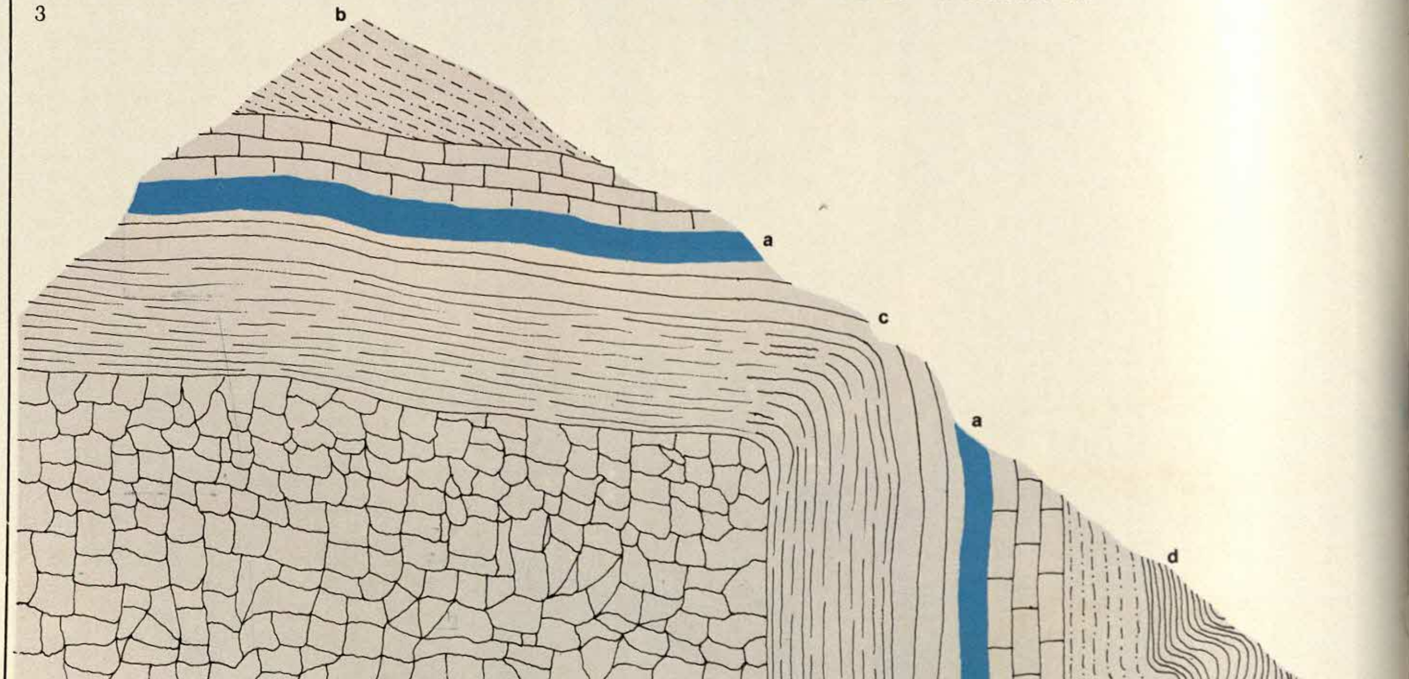


THE EROSION OF A MONOCLINAL FOLD—A monoclinal fold such as that in Illustration 2 is formed by the lifting of a section of the Earth's crust. The part that is lifted is subjected to intense and rapid erosion. Sometimes it is eroded to such an extent that the central part of the folded stratum **aa** is uncovered. In this case, a succession of types of rock are emerging from the side of the eroded structure between **b** and **c.** These are repeated symmetrically between c and **d.** Only the upper elbow of the fold is visible; the lower elbow is hidden in the depths of the Earth, inaccessible except by drilling, as when in search of oil.

3

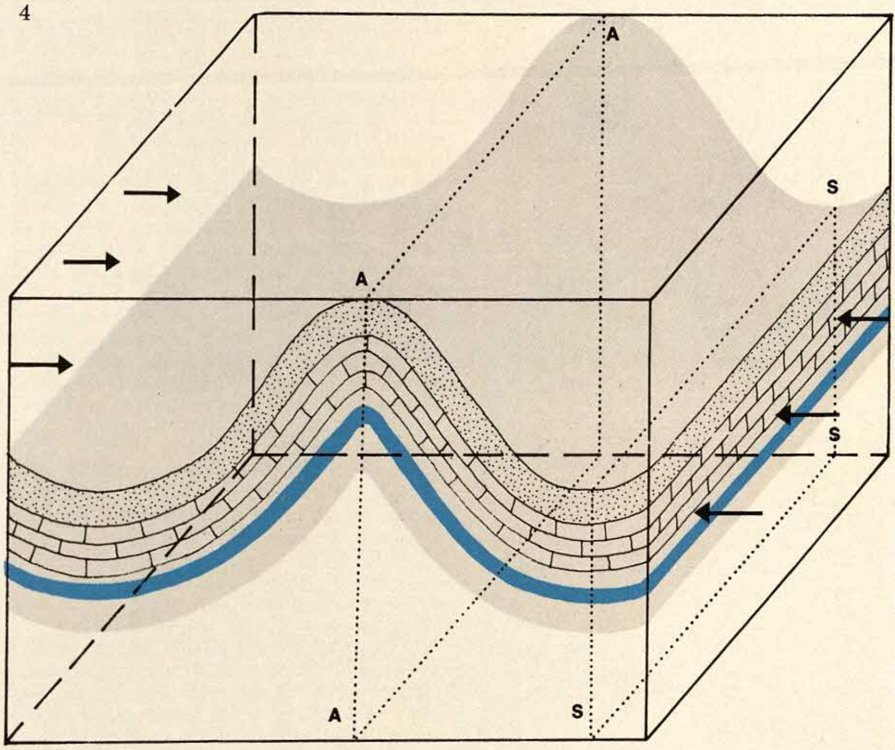


THE COMPLETE FOLD—If a collection of rock strata were exposed to a regularly exerted compression in the direction of the arrows in the illustration, the strata would bend and form undulations like waves on a body of water after the wind that has whipped it up has died down. In this case, the waves have a fine, regular shape. Such folds, which are called complete, are simply composed of two easily distinguished parts. The high part—the crest of the wave—is anticlinal. The low part—the wave's trough—is synclinal. A vertical plane drawn through the upper part of the anticline cuts it exactly in half; this is called the axial plane **AAAA** of the anticline. The axial plane of the syncline **SSSS** is similarly established. These planes are shown in the illustration as two rectangles. The upper horizontal edge of these rectangles is called the axis of the anticline or syncline. Toward the crest of the anticline or the trough of the syncline, the curvature of the strata is greatest. This point is called the hinge of the fold.

If the strata are of sedimentary origin, the lower ones were deposited first—that is, they are the oldest.

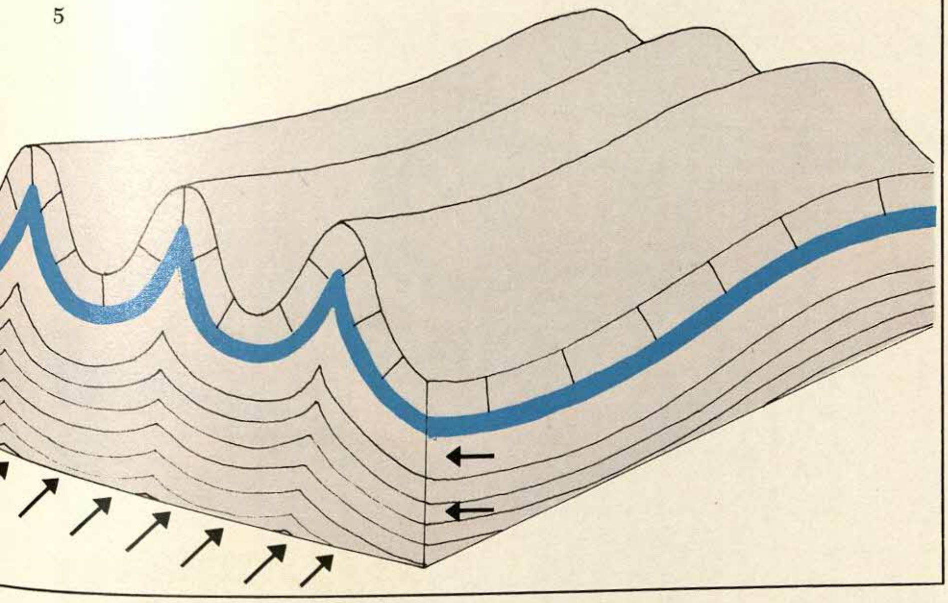
A fold of this type—the axis **AA** of the anticline or **SS** of the syncline—may extend for a few kilometers, or it may go on for hundreds of kilometers. It stops where the forces that pushed the rock sideways to form the fold (forces that sometimes give rise to great mountain chains) stopped exerting their pressure.

4



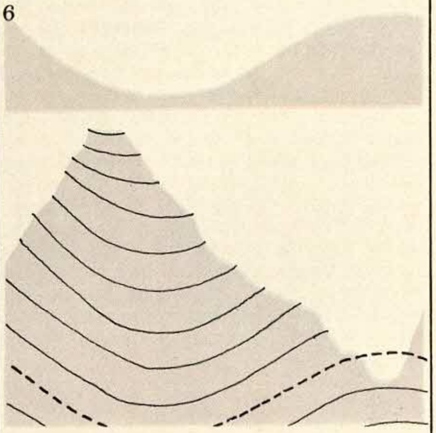
AXIAL UNDULATIONS IN A SERIES OF FOLDS—A long fold may have wave shapes on its axis—these are called axial undulations. They are formed by forces exerted in the direction indicated by the arrows.

5



FOLDS AND EROSION—It may seem that anticlines of complete folds correspond to the crests of mountain chains, and that synclines form their valleys. This is true only in rare cases. Anticlines appear on the axis of a fracture along which water has been able to infiltrate. In a mountain system, the anticlines thus often form the troughs and valleys, while the synclines are the crests.

6



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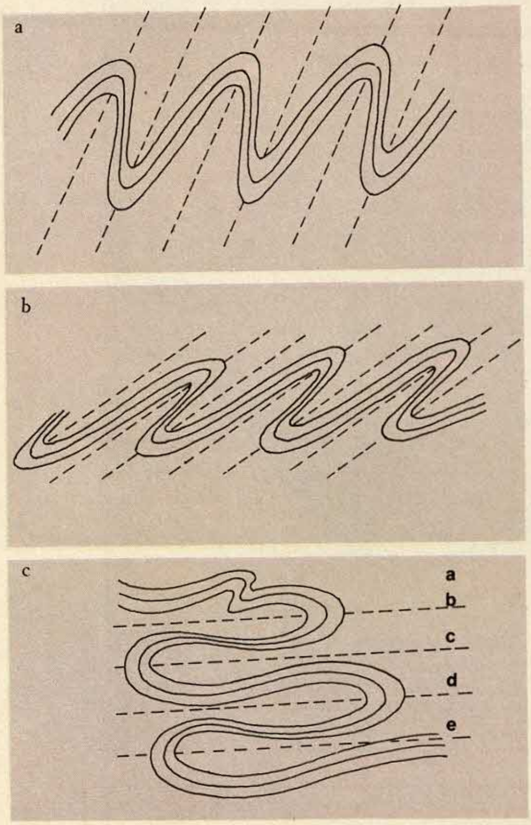


VARIOUS POSITIONS OF FOLDS—A fold such as that in Illustration 4 is rare. Instead of being vertical, the axial plane is often angled or even horizontal. It is important to identify these folds, since they may affect the estimate of the chronological succession of layers of successively deeper strata.

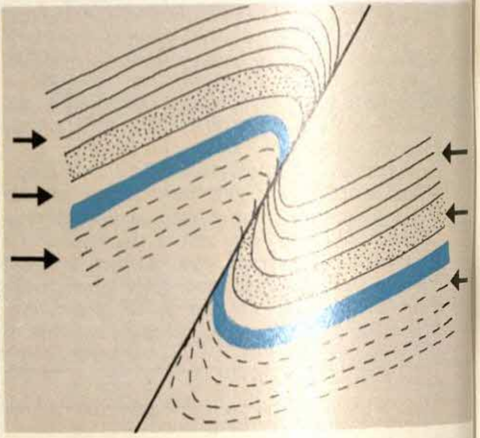
A fold with an axial plane that is slightly inclined from the vertical is called an inclined fold (Illustration 7a). Such an inclination may have perfectly vertical strata on one flank, while the strata on the other flank are at a mild angle.

A very great inclination of the axial plane forms a recumbent fold, or overfold, in which both flanks lie at a very sharp angle (Illustration 7b). Recumbent folds, which must have undergone intense movement, have an asymmetrical form. One of the flanks may be stretched out more than the other.

If the inclination of the axial plane is less than 45°, a fold is reversed, or overturned (Illustration 7c). A vertical hole bored through a series of reversed folds will pass through the strata of the subsoil in the order in which they were deposited in some stretches, and in the reverse order in others. In stretch **ab,** for example, the most recent strata are on top, the most ancient on the bottom. In **bc,** however, the strata—which are the same as in **ab**—are in the opposite order. In **cd,** the order is again direct; in **de** the order is reversed. Usually, the deeper a geologist digs, the greater his hopes of uncovering ancient rocks. He must be very careful in studying the strata of a reversed fold; its formation could deceive him as to relative ages of the strata.

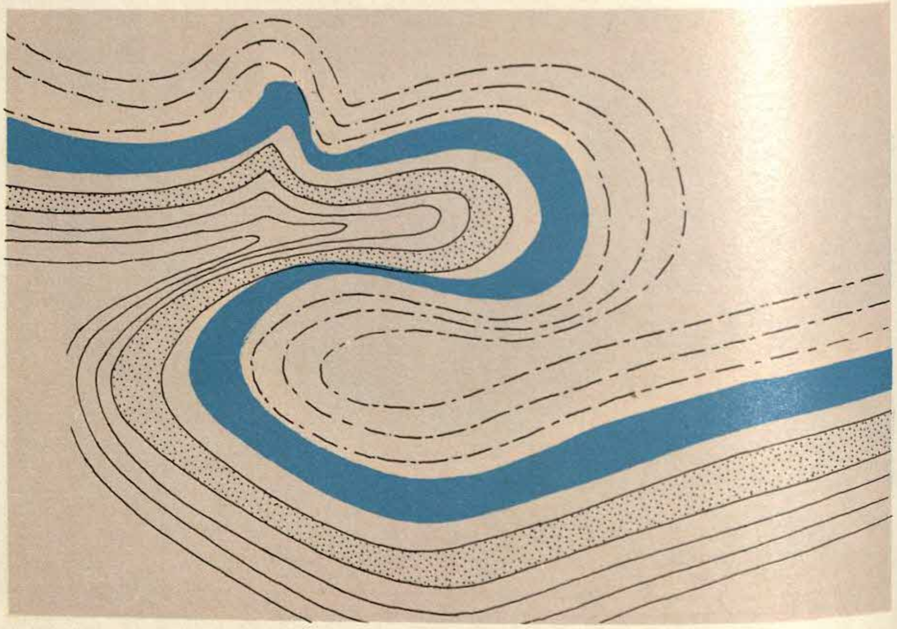
FAULTS—When the forces creating a fold are exerted (as shown by the arrows) in a relatively short time, the rocks do not have time to change shape. A fracture appears along the axial plane of the anticline, and the rocky strata slip out of alignment with one another. This type of fracture is called a fault. Faults are a phenomenon of great geological importance; they are the cause of many earthquakes. A fold may be complicated by the presence of a fault. Faults are found in areas that are generally less buckled than those shown here. Faults range in size from those that are detected only under the microscope to others that are hundreds of miles long. Some fault zones are composed of countless individual faults that occupy a wide belt.

8



OVERFOLDS—Extreme cases of folding place the strata of the ground on top of one another, hiding the layers beneath the fold. This phenomenon is often found in very deep rocks, which are subjected to very high temperatures and pressures. Such deformations, called overfolds because they fold over the underlying strata, are fairly common. Overfolds are responsible for the formation of entire mountain chains. Many of the crests and peaks of the Alps are large folds that have folded over the older strata lying underneath. These large overfolds are not as simple as shown in the illustration. In the Alps, such overfolds stretch for hundreds of kilometers and are complicated by other phenomena, such as faults, slips, buckling on the sides of the folds, and undulations. The arrangement of the rocks in a region, and the location of such phenomena as folds and faults, are called the tectonic characteristics of the region (from the Greek *tektos,* meaning "structure").

9



FAULTS | fractures and displacements of the Earth's crust

1

COOLING FRACTURES—These basaltic rocks, which originated from the solidification of lava, have contracted and split. The mass of the lava flow had certain dimensions when the volcano stopped erupting. As this material cooled through a range of almost 1,000° C, the contractions produced many fractures, breaking the rock into large blocks shaped like hexagonal prisms. The photograph (Illustration 1) shows the fractured basalts of Acquapendente, Viterbo, in Italy.

The rocky crust of the Earth is rigid, but at the same time flexible. It may bend and fold in complex ways when the tectonic forces acting on it are not of great intensity and are applied for a very long period of time. Often, however, the rocks forming the Earth's crust are subjected to extremely intense pressures, or they move with great suddenness. Then, instead of being distorted in a plastic fashion, the rocks break.

Fractures in the Earth's crust testify to the speed with which various movements of the crust may occur. Both the forms and the causes of fractures vary greatly.

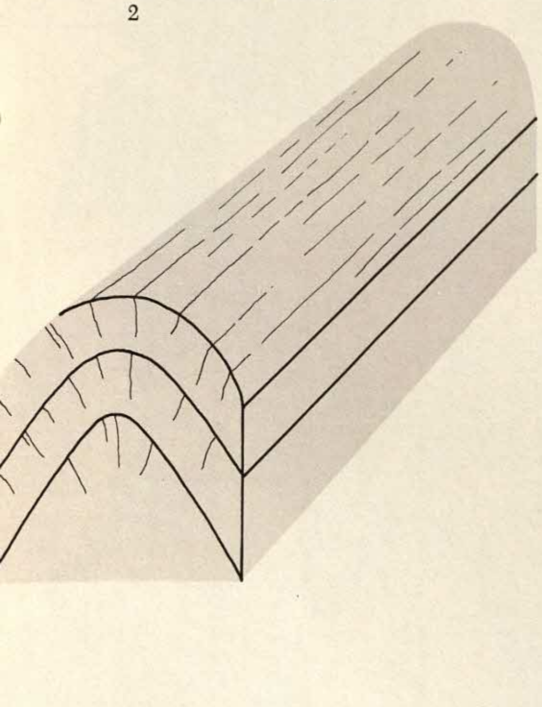
A rock may fracture as a result of cooling; the lowering of the temperature causes the rock to contract and break; or, a rock may break because it has been subjected to mechanical stress. Some fractures are very small, a few millimeters wide and a few centimeters long, but others are many kilometers long and several meters wide.

A geologic fault is produced wherever the rock strata on one side of a fracture or fissure are displaced or moved in any direction with respect to the strata on the opposite side of the fracture. The movement following the opening of the fault may occur rapidly and stop immediately, or it may continue in fits and starts for fairly long periods of time; the displacement may be slight or extreme.

The identification or localization of faults is important in both pure and applied science. The stratigrapher, for example, must be able to recognize faults or else take the risk of misinterpreting the strata under study. Moreover, to the geologist, a fault may signify a move-

TENSION FRACTURES — The plasticity of rocks in the Earth's crust allows them to be distorted, even into very tight folds. However, if the folds are too tight, or if they were formed too quickly for the rock to undergo a plastic deformation, then the folds may suffer multiple fractures due to the excessive tension to which the rock has been subjected.

2



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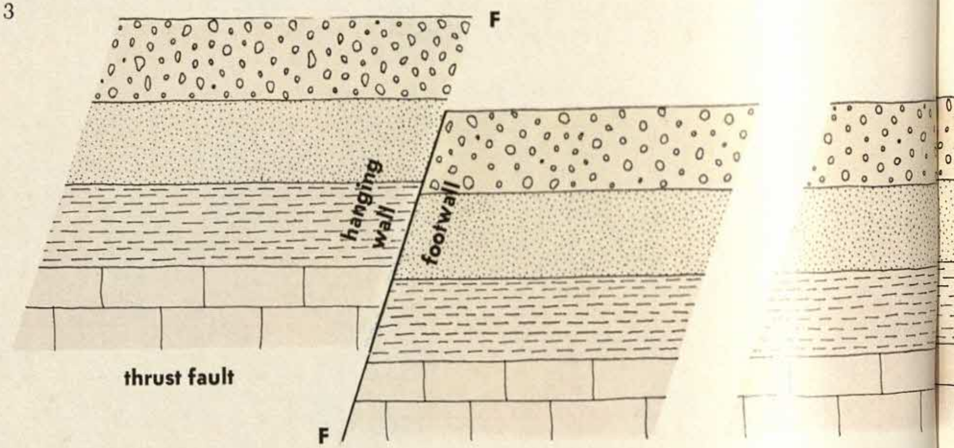


FAULTS—The term "fault" is used in geology to refer to fractures in the Earth's rocky crust, whatever their dimensions, that are accompanied by a shift or displacement of one of the two faces of the fracture plane. Line **FF** in the diagram denotes a fault plane, or a plane along which the fracture of the strata occurred. As the illustration shows, in most cases the fracture plane is oblique, both with respect to the direction of the strata contacts and with respect to the vertical. The fracture thus divides the rock into two parts with one part overhanging the other; this is the hanging wall. The other part, located below the fault plane, is

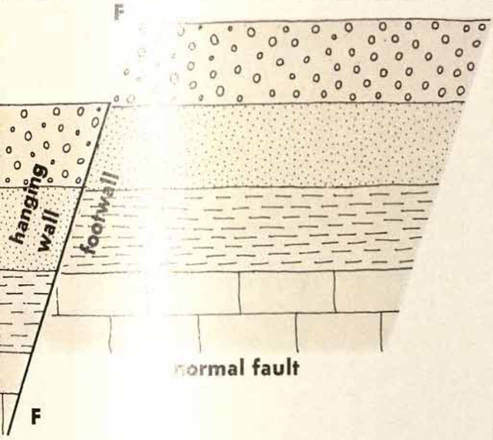
A FAULT MIRROR—Often the friction occurring when rocks slip across a fault plane produces a kind of abrasion that makes the rocks shiny and mirror-like. The fault plane is then called a fault mirror, and the polished rock faces are called slickensides. For this phenomenon to occur, erosion must have removed the rocks on one side of the "mirror."

4

ment that either is going on presently or took place in the past. The fault enables him to interpret the geological history of the area under examination. In technical applications, knowledge of the existence of faults in the Earth's crust is of fundamental importance, because they indicate movements of rock that cannot be halted by human constructions. If, for example, a bridge were to be built across an active fault, or if a large dam were to be constructed on faulted terrain, the construction would be irremediably condemned to destruction with probable catastrophic consequences. A geologist studying areas where these colossal structures are to be erected must ascertain whether or not there are any traces of movements within the Earth's crust.

Sometimes a fault is visible to the naked eye—as when its fracture plane comes to the surface. Sometimes, a fault is completely invisible and hidden in the subsoil. If a tunnel or some other construction is to be built so as to pass through the subsoil, it is the geophysicist's task to find hidden faults; to do this, he studies Earth tremors that are produced artificially by means of explosions.

The shape of a tunnel, for example, is partly determined by the stress conditions in the ground. If the horizontal pressures are much smaller than the vertical, the height of the tunnel should exceed the width; the opposite is preferable if the horizontal pressures are the greater. The latter condition may prevail in rock masses that have been subjected to major tectonic disturbances.



the footwall. Generally speaking, two types of faults exist. One type (normal fault), illustrated on the right, is characterized by a downward movement of the hanging wall block. The other (reverse or thrust fault), on the left, is marked by an upward shifting of the hanging wall block.

MOVEMENT OF A FAULT—This illustration shows the movement of two blocks of rock separated by a fault plane. There has been not only a slip in the vertical plane—with one of the two blocks rising or dropping—but also a horizontal movement. Sometimes a rotary movement also occurs. The opening of a fault in a block of rock always takes place abruptly and causes a shift of the two, sometimes huge, rocky masses. The shock spreads through the surrounding rocks, giving rise to greater or lesser Earth tremors according to the magnitude of the phenomenon. As soon as the fault has formed, the tensions in the crust that produced it are relieved; but the factors that brought about the fracturing may continue and, with time, may provoke new shifts of the fault blocks. In mine tunnels crossed by faults, precise checks must be made to avoid sudden collapses.

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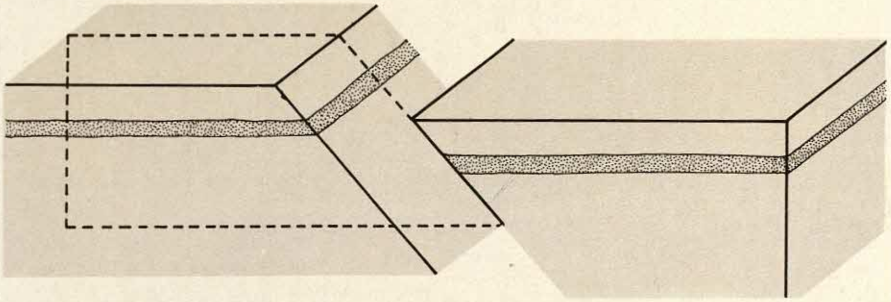
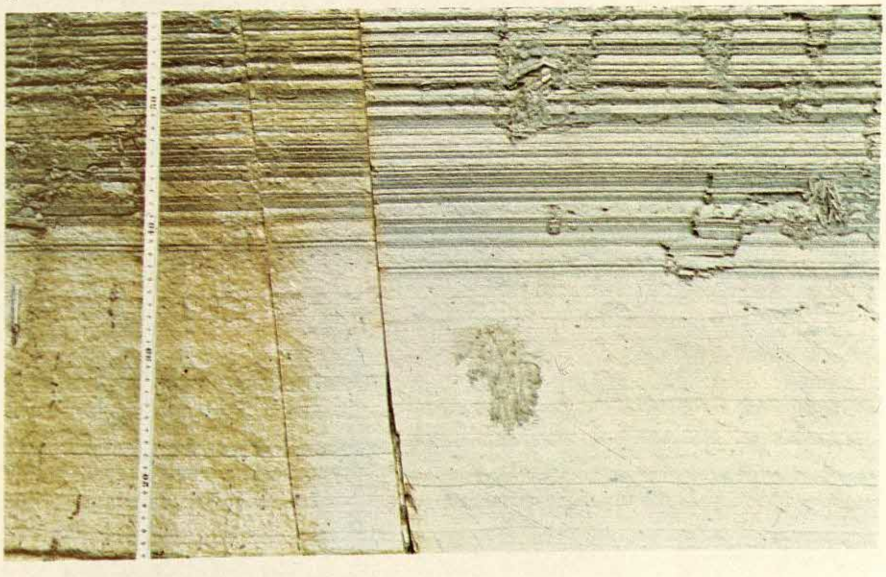


FAULT BRECCIA—Friction between the walls of a fault may cause a great amount of material to be broken from the walls; this material falls into the fissure, filling it. If the broken material consists of discrete pieces, it is called fault breccia; if, on the other hand, the material is ground very fine, it is called gouge. Ordinarily, the material filling the fissure has the same composition as the rocks in which the fault was opened.

Sometimes the sudden opening of a fault permits water to rise toward the surface, carrying with it minerals that are deposited in the fault. This explains why a spring may suddenly appear in an area that was previously without water; it also explains why cementing minerals and even minerals that are useful enough to mine may be found among the fault breccia.

This illustration shows breccia beginning to form in a small, almost rectilinear fault. If movements continue through time, other material from the fractured walls will be transformed into breccia.

6



7

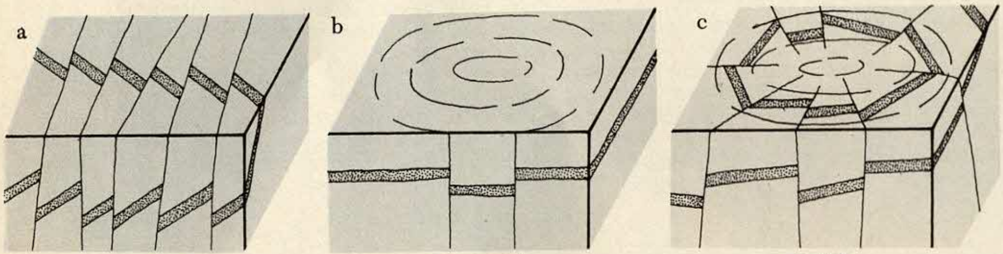
FAULT ASSOCIATIONS—The forces that have produced one fault may often open other faults near the first. Often a simple fault is also made up of two or more sections located very close to each other. So-called associations constitute a phenomenon that deserves special study. The way in which faults are associated often provides clues as to their origins.

Parallel faults (Illustration 7a) have almost the same orientation, being arranged more or less parallel to one another.

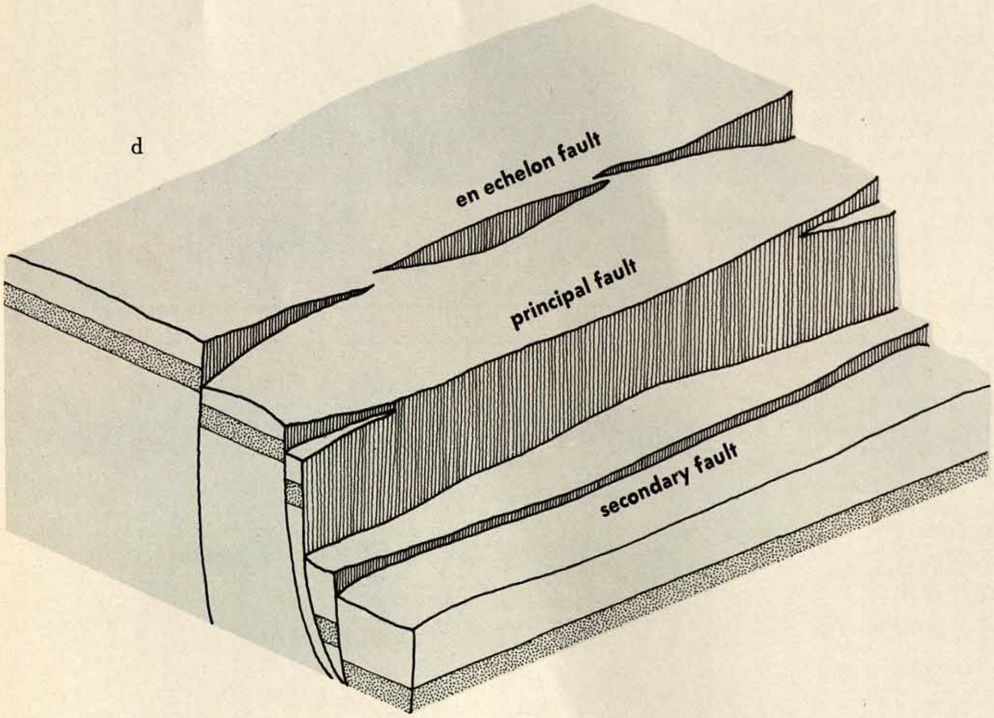
Concentric faults (Illustration 7b) are arranged in a more or less regular fashion as the arcs of concentric circles.

Radial faults (Illustration 7c) constitute a system of faults converging on the same point. These may be added to a system of concentric faults. In the case illustrated, the point is the center of the preceding system.

En echelon faults (Illustration 7d) make up systems of almost parallel faults that are short in length and arranged in shinglelike fashion. This illustration shows, in addition to the en echelon fault, a fault said to be the principal fault because it has greater "throw" than the secondary faults. The throw is the slip or displacement along the fault plane.



parallel **concentric** **radial**



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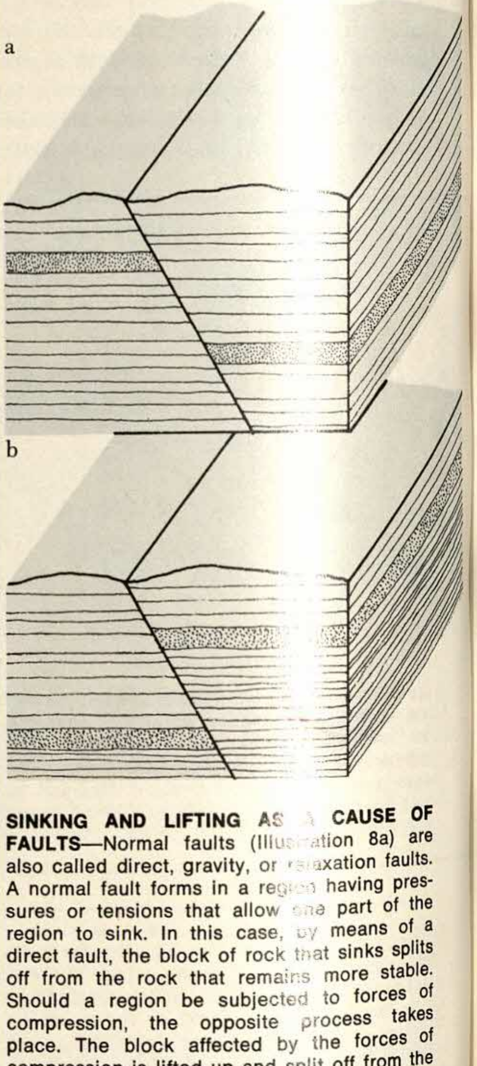
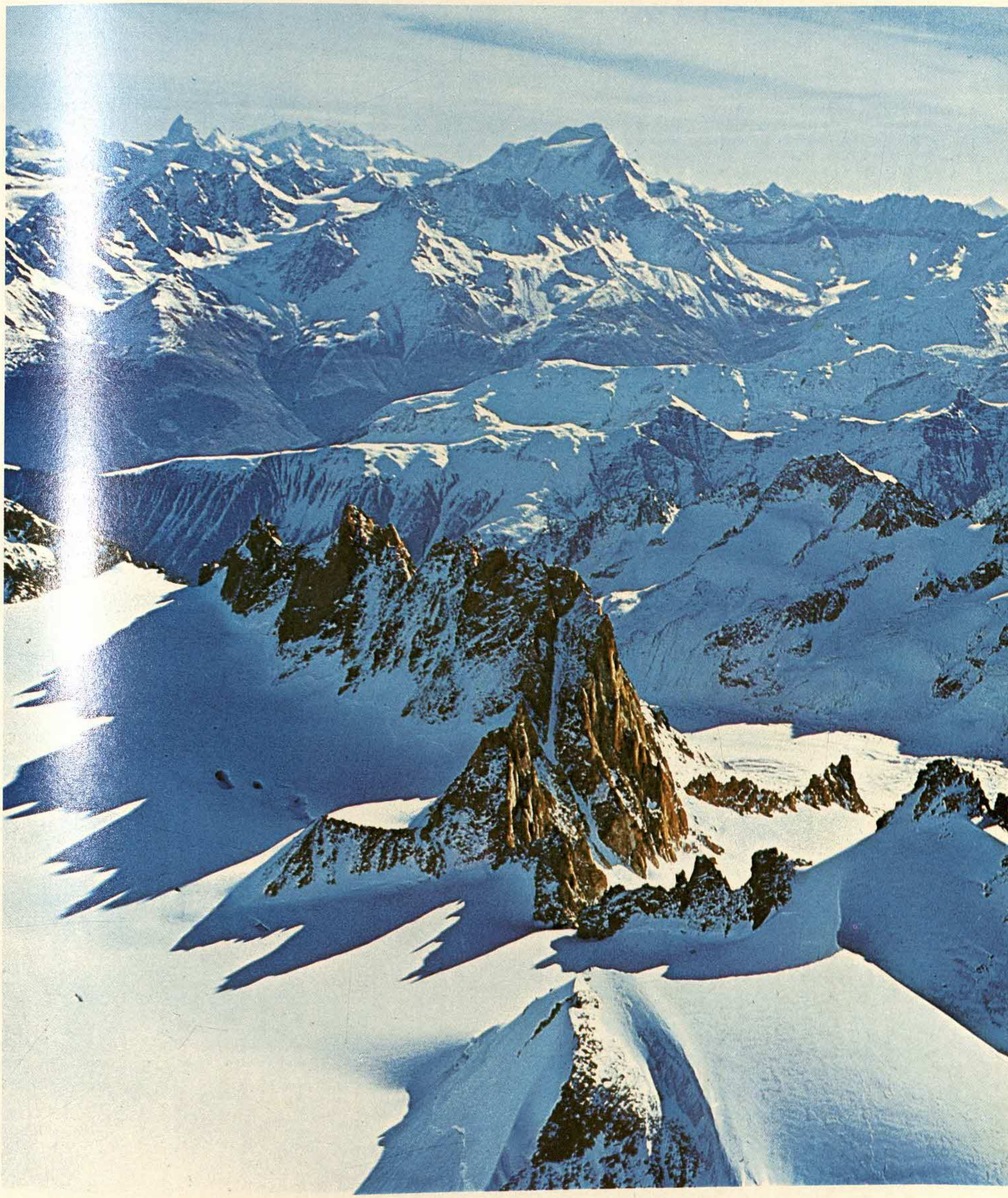


SINKING AND LIFTING AS A CAUSE OF FAULTS—Normal faults (Illustration 8a) are also called direct, gravity, or relaxation faults. A normal fault forms in a region having pressures or tensions that allow one part of the region to sink. In this case, by means of a direct fault, the block of rock that sinks splits off from the rock that remains more stable. Should a region be subjected to forces of compression, the opposite process takes place. The block affected by the forces of compression is lifted up and split off from the block that transmits the compression by means of reverse faults (Illustration 8b).

This structural style in faults is found in the great tectonic grabens (or down-dropped blocks) and horsts (uplifted blocks) throughout the world. The phenomenon is particularly noticeable in the Rhine trough, in the pillars of the Vosges, and on the edges of the great African rifts.

OVERFOLDS | overlapping rock formations

1



A GRANDIOSE OVERFOLD: THE ALPS—The formidable pressures that lifted the majestic chain of the Alps (Illustration 1) out of the sea simultaneously caused the buckling of the rocks into folds that cover the underlying ground. The erosion that is now eating into the valleys strips bare the rock strata, revealing the past history of this amazing phenomenon.

The Earth's crust is subjected incessantly to powerful forces that cause distortion and vast movement. Even casual observation of the arrangement of rock strata testifies to these geological phenomena. Changes were taking place continually in the past, and they are taking place today, causing profound alterations in the terrestrial crust. Earthquakes are striking evidence of these changes.

In most cases, earthquakes are caused by fractures resulting from stresses in the rocks. These forces can be vast and potent, sometimes building up folds hundreds of kilometers long and gradually pushing them over the underlying rock strata over a period of millions of years.

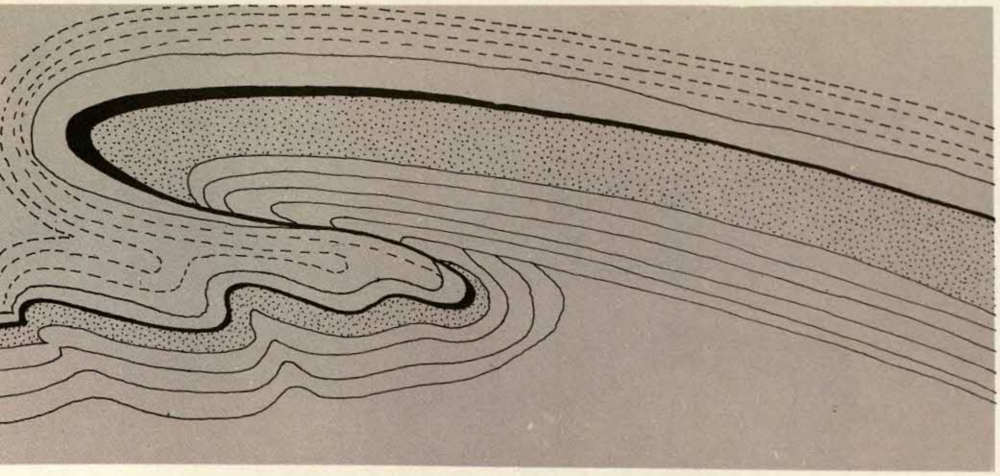
THE GREAT OVERFOLD STRATA

Simply stated, orogenesis is the phenomenon by which a great mountain chain arises. For example, a huge, continent-sized block of rock may be subjected to enormous pressures from opposite sides, causing the part subjected to compression to bend upward. This was the case with the Alps, which were forced up by the thrust of Africa against central Europe. It was also the case with the Himalayas, which were pushed against the center of Asia by the movement of the Indian subcontinent. (A subcontinent is a large and somewhat isolated peripheral region of a continent.)

THE LISTRIC WEDGE—One variation in the formation of a fold is the listric wedge. Sometimes, horizontal pressures push a rock mass out of shape (Illustration 3a) and fracture it obliquely, separating a wedge-shaped area, which slips across the underlying ground (Illustration 3b). As it slips, the layers of rock covering the wedge—layers that are softer and more malleable—change shape. The rocks of the wedge, which are more fragile, fracture as the movement continues (Illustration 3c). The layers into which the wedge is subdivided may also slip across one another. The whole mass of rock may then undergo erosion, which bites deeply into it, creating a vast array of shapes.

THE FORMATION OF AN OVERFOLD—The rock strata at the top are parallel and horizontal. The forces that transform them also work in a horizontal direction. In the course of time, these forces cause a buckling of the rock strata, causing a series of folds of varying sizes. One of the folds stretches out and covers the anticline (the crest of the fold) on its left with a layer of rock. As the action of the horizontal forces continues through time, the layer expands and covers a fairly large area. The layer of the fold and the ground it has covered are buckled in their turn into further folds. Erosion works on the overfold and digs deeply into the rock mass, removing part of the fold and exposing vestiges of the phenomenon, which can be identified only by studying the arrangement and types of rock strata on the sides and peaks of the mountains. The overfolding and the formation of the stratum usually take place at a very great depth.

2



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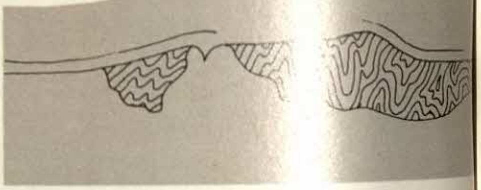

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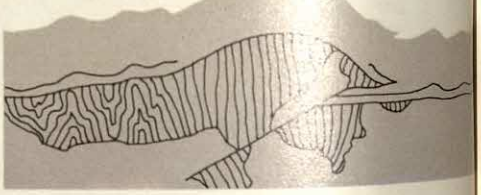

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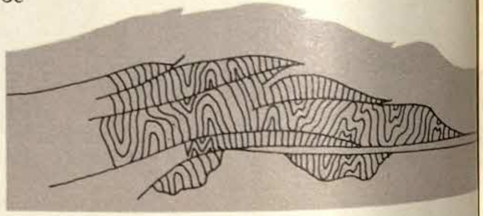
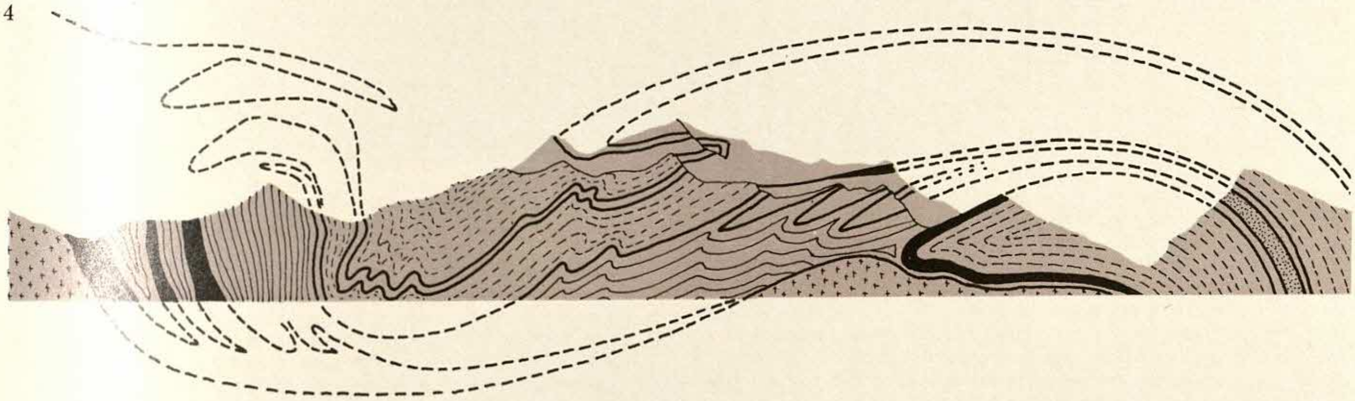


THE MONTE LEONE FOLD—At the end of the last century the digging of the Simplon tunnel in the Alps made it possible for geologists to study samples of rock taken from deep inside the mountainous mass. Their studies confirmed the presence of an extensive overfold. The central part of the Monte Leone rock mass is made up of a fold that extends from Val d'Ossola in Italy all the way to the Rhone valley. The heavy lines show the rock strata; the dotted lines indicate how they would continue into the space that has been eroded.

4



Actually, the phenomenon is much more complex. The thrust of the continental masses not only bends up the rocks to form new mountains, but also causes an intense buckling of the deeper rock strata. For example, at a depth of about 10 km, temperature and pressure conditions are such as to cause extreme folding of the rocks, distorting them without an excessive number of fractures.

The rocks that today form the Alps have undergone these immense pressures—this can be deduced from a study of their composition. A great many of them are recrystallized, having undergone metamorphism—that is, their original crystalline structure has been changed. Those eruptive rocks in the Alps that have not undergone modification are almost exclusively the plutonic rocks that were formed in the period after the mountain chain was forced up. Magma rose and solidified into rocks without being profoundly altered by pressures and distortions.

The rocks forming that part of the Earth's crust that was lifted up during the formation of the Alps have generally suffered metamorphism from the same forces as those that created the Alpine chain. Over the geological eras, this phenomenon, caused principally by watercourses flowing over the Earth's crust, has dug deeply into the continents. Because rain and snow feeding these watercourses are more abundant in higher areas, the erosion is proportionately more rapid in such areas. Only a sinking of the crust could reduce the action of the watercourses, making it less intense and violent and slowing down the erosion.

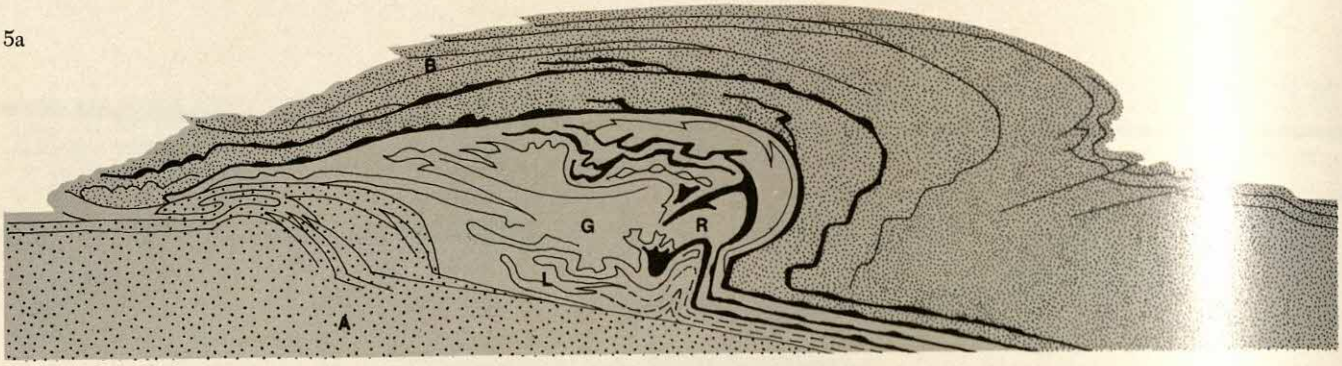
While the Alps were being forced up, erosion did not wait for the end of the process before beginning its work. It started as soon as the orogenic thrust lifted the Earth's crust out of the sea, and it became more intense as the mountain chain became higher. Thus, it is not only today that the Alps are being eroded; water and ice have been wearing them away continually for tens of millions of years. When the movement that created these mountains began, their present surfaces were far below where they are today—in some cases as much as 10 km, even though they do not stand that high today. The history of the phenomena that took place within the Earth during the appearance of the Alps can be read on the rocks of mountainsides that have been stripped bare by erosion.

Very often, rocky masses of the subsoil extending over large areas have the same, or very similar, characteristics (chemical composition, crystalline structure, and so forth). When these masses have been pushed up and then stripped bare by erosion, individual strata can be traced for great distances. Sometimes, when erosion has left only a thin stratum, these rocks form the only peaks of a mountain chain, or an isolated peak within an area that was once covered by an entire stratum of rock.

Studies of these rocks at various depths have shown that the same rocks were sometimes folded over and over again, covering underlying rock layers. This may be compared to a bed covered with a quilt, a blanket, and a sheet, with the coverings folded down and over, somewhat like a Z. On top would be the quilt, then the blanket, then the sheet. Next are sheet, blanket, quilt; then again quilt, blanket, sheet. At the bottom, the sheet is in contact with the mattress, which represents the underlying rock.

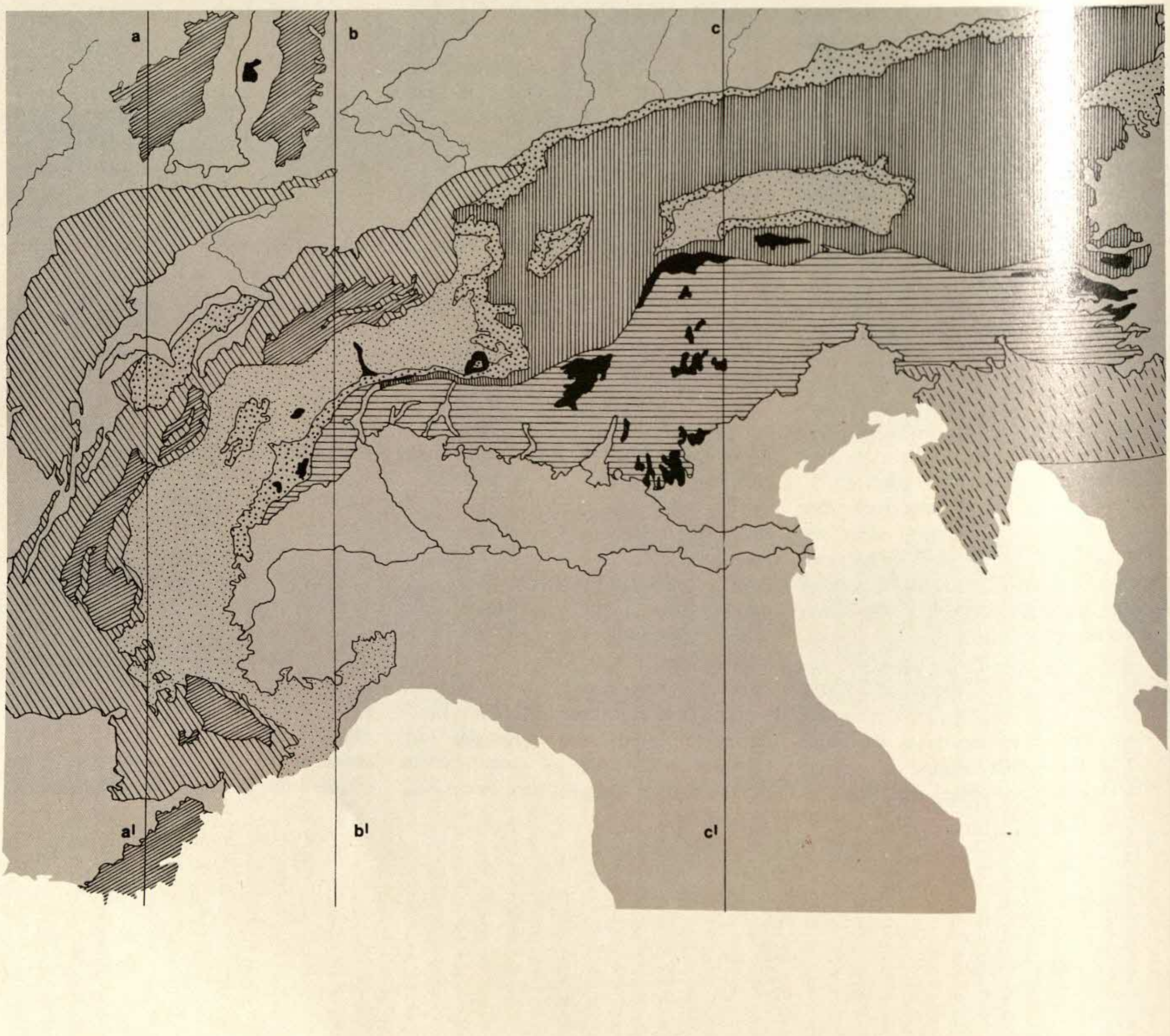
The entire Alpine chain is made up of these enormous folds. In some of the Alpine massifs—in particular, the Monte Leone at the Simplon Pass—erosion has revealed the history of the overfold.

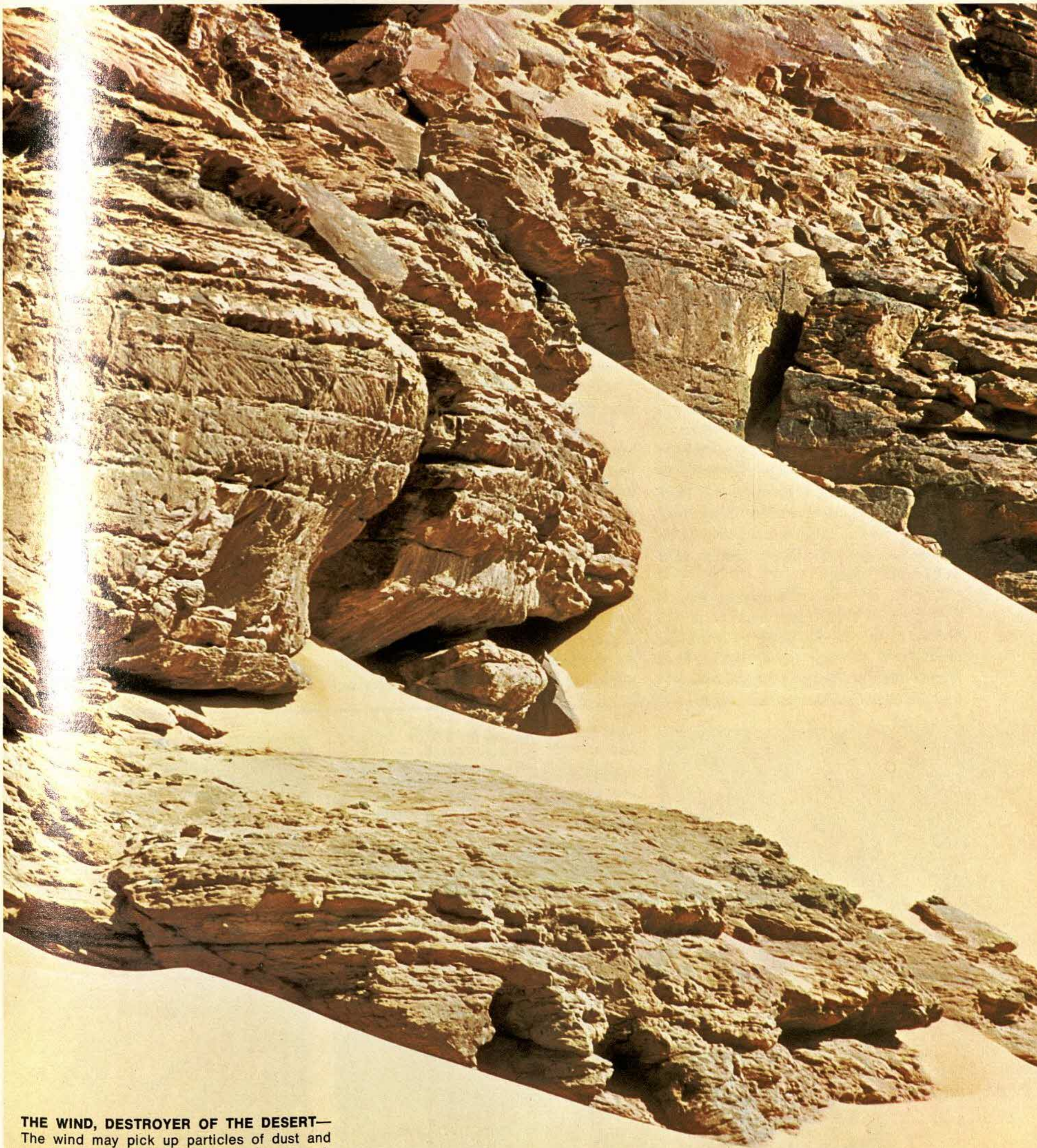
5a



THE TECTONIC SECTION OF THE ALPS—Illustration 5a is a section of the Alpine massif with a plane running from north to south. Onto this plane are projected all the folds and overfolds in all the north-south sections throughout the entire massif from the Piedmont region of Italy to Austria (**aa′**, **bb′**, **cc′** in Illustration 5b). **A** is the rock formation that forms the base of the Alpine massif, across which the mass of the Alps has slipped. **B** is the mass of southern rocks that have bent to form the giant overfold. Originally located in the south of the region now occupied by the massif, these rocks ended up in Switzerland. The overfold has imprisoned other rocks between the underlying ground and the fold itself. By superimposing the profiles of the various north-south sections of the Alps on Illustration 5b, the effects of erosion on the overfold and various depths of the underlying rocks is evident. For example, at **L** are the peaks of the mountains that now stand around Monte Leone, where erosion has eaten away all the overlying rocks. At **R** are the rocks forming the Monte Rosa massif, and at **G** those forming the Great Saint Bernard. The complex structure in the central part of the illustration shows that the Alpine overfold has had profound effects on the rocks which have undergone extremely complex overfolding processes that cannot be fully identified.

5b





THE WIND, DESTROYER OF THE DESERT— The wind may pick up particles of dust and sand and hurl them with violent, abrasive effects against rocks. This type of erosion is quite common in hot, arid regions, such as the Egyptian desert shown in this photograph.

The face of the Earth undergoes continual change. Orogenetic and plutonic processes act primarily to raise portions of the Earth's crust, while the processes of erosion tend to level the land, degrading or wearing down the surface in some places and aggrading or building up the surface in other places.

An understanding of the processes of erosion is important for many reasons. First of all, erosive processes determine the appearance of the landscape—the steepness of a rocky cliff; the depth of a gorge where a torrent flows; the soft roundness of a hilly countryside; the twisting course of a river as it nears its mouth; the perfect arc of a beach between two headlands; the profile of a section of a valley; and the furrows that cut into the side of a mountain.

The study of erosion, together with the study of tectonics or diastrophism, provides a useful interpretation of the morphology of the soil as well as an appreciation of the various forms observed in the landscape. Moreover, the study of erosion is important from the point of view of conservation, for men can exercise at least partial control over these processes which have so much impact on the lives—especially the economic lives—of human beings.

Finally, an understanding of erosion is important to an appreciation of the history of life on the Earth, because the imprints or remains of organisms from remote eras of the past have been preserved in certain rocks of the Earth's crust. Obviously, the remains of early organisms are not found in lava or igneous rocks, which originated as magma (hot, molten material) deep inside the Earth. Rather they are found in sedimentary rocks, rocks formed from the sediments and fragments of other, older rocks. The determining factor in the formation of sedimentary rocks is erosion, that combination of phenomena that crumbles and destroys rocks and produces an accretion of sediments and fragments at some distance from the original rocks.

Before studying the life of the past as it is revealed by fossils imbedded in sedimentary rocks, it is necessary to study the causes and processes of erosion in order to learn how the various agents of erosion work to model the landscape of this planet.

EXAMPLES OF EROSION

Many sedimentary rocks are found in the Alps, that great European mountain system that arose some tens of millions of years ago. Today, many Alpine summits are composed of rocks that once were buried under strata several kilometers thick. These rocks have been exposed by the relentless erosion of the covering layers.

The processes of erosion may wear down the rocks at the rate of about 0.1 millimeter (twice the thickness of a human hair) each year. At this rate, a mountain may be reduced 10 centimeters in a millennium, a hundred meters every million years, a kilometer every ten million years—in much less time, therefore, than has elapsed since the Alps were formed. In many other cases, erosion acts much more rapidly.

The most important valleys of the Alps—such as the Valtellina, the Val d'Aosta, and the Ticano Valley—were excavated to depths of more than 2,000 m (about 6,500 ft) between the rocks of the mountains in less than a million years. It is quite obvious that most of the erosion in these valleys took place during the period when they were filled with glacial ice; therefore the erosion must have cut away several millimeters of rock each year.

Everywhere in the landscape the effects of erosion are apparent. At first, it might seem that the phenomena of erosion are absent in a large plain such as the Po Valley in Italy. The valley floor, however, consists of an accumulation of erosion debris from the Alps, an accumulation that has filled in a sea no less.

The extraordinary proportions of erosive phenomena indicate indirectly the continuing action of orogeny: if mountain building had ceased even 50 million years ago, the land of the Earth by now would have been reduced to an enormous plain only a few meters above sea level. Orogeny has not occurred in some areas of the Earth—northern Can-

FREEZING—When the water trapped in pores and fissures of rocks freezes, it expands in volume and may break rocks of considerable thickness.

HEAT—Radiant energy from the sun is an agent of weathering or thermal erosion; it crumbles rocks by causing them to expand.

ada, for example—since times geologically quite remote; in these places, in fact, the ground is perfectly flat and only slightly above sea level.

The history of the Earth, then is a story of a succession of risings of the crust and a continuous destruction of elevations, whose debris, reduced to small particles and carried to the sea, has formed deposits of considerable thickness.

SOLAR ENERGY VS. TERRESTRIAL ENERGY

The struggle between orogenetic phenomena and erosion is actually a struggle between solar energy and terrestrial energy. A map or diagram of the solar system might suggest that the planets are located far away from the sun, beyond its influence or, at best, receiving a precisely measured quantity of radiation that, in the case of the Earth, permits the regular development of life. Geologically speaking, solar energy is extremely important for it is the principal agent in the destruction of the surface contours of the Earth. The energy expended in the formation of mountains is terrestrial energy, resulting from the heat of the planet's interior, energy that causes movements of the Earth's mantle (sima layer). This heat derives from the Earth itself. The energy that produces destructive phenomena, particularly erosion, is of solar origin. The sun is the moving force behind the Earth's weather, the source of energy that produces the winds (which drive ocean waves against the coasts), and the source of energy that causes moisture to be evaporated from the surface and later to be precipitated onto that surface.

If it were not for the heating effects of the sun, erosion would cease entirely or, at least, be diminished considerably. Whether or not this will actually happen in the distant future is unknown. Scientists do know, however, that the sun is destined eventually to undergo a period of hundreds of millions of years of continual cooling. If orogenetic activity were to cease prior to that cooling, the Earth would soon appear to be a dead body, similar to the moon. If, on the other hand, orogenetic activity were to continue, rugged features would be formed, and these features would endure until the very end of the planet's existence.

PRINCIPAL AGENTS OF EROSION

Erosion consists of several phases, the first of which involves the destruction of a rocky formation, the breaking off of particles and fragments of rock. The second phase involves the removal of these particles and fragments from their place of origin, and the final phase involves the deposition of these materials at some other location on the Earth. Some geologists prefer to consider only the last two phases as erosive processes; the first phase, the disintegration of rocks, they treat under the heading of "weathering."

Erosion is a complex process that may involve a number of different agents. Some agents, such as running water and glacial ice, are of tremendous importance because they produce rapid destruction of mountain formations. Other agents, because they work more slowly and produce only slight erosion, are considered of secondary importance. The principal agents of erosion are discussed briefly in subsequent paragraphs.

As mentioned previously, heat from the sun is an important agent of erosion. In addition to its role as weather maker, solar energy acts directly on rocks. During daylight hours, rocks absorb radiant energy from the sun and tend to expand. As the sun sets and the heat energy in the rocks is lost to the atmosphere, the rocks become cooler and begin to contract. Repeated heating and cooling—repeated expansion and contraction—can cause the rocks to crack and break into fragments. Other erosive agents then can enlarge the cracks and carry away the debris. The action of solar energy on rocks is most apparent in hot, arid regions, where the actions of other agents are less noticeable. Erosion is faster where the temperature change is extreme.

In cooler regions, freezing plays a role in the destruction of rocks. Most rocks are porous, and minute quantities of

SOLUBLE ROCKS—Water seeping and flowing through soluble rocks can open its own passages and create magnificent grottoes.

BLUE MESA, ARIZONA—The appearance of this region can be attributed to the erosion of the rock formation.

GRAVITY—The force of gravity can cause erosion of loose rocks and other materials from mountains.

water can seep into the pores. When the water freezes, it expands in volume and, acting like a wedge, splits the rocks. Subsequently, the ice melts, water seeps further into the cracks, and the process may be repeated. Thus, through the action of alternate freezing and thawing, rocks may be fragmented and destroyed; the debris then may be carried off by running water. Residents of many cities in the northern half of the United States find frequent evidence of this kind of destruction in the chuckholes that develop rapidly in their streets and highways in the wintertime.

Rocks are also affected by chemical changes. Water running over the surfaces of rocks and penetrating them deeply may dissolve the crystalline components of these rocks or chemically alter the rocks themselves, destroying them in the process.

Wind is another important agent of erosion. The wind itself does not erode; however, when it blows strongly, it may pick up dust and soil particles and cast these particles against rocks, wearing the rocks down as through the use of a fine abrasive. The erosive action of the wind is greatest near ground level, because the small dust and rock particles cannot be carried to any great altitude.

After rock masses have been raised by mountain-building activities and after erosive processes have cut into these masses, the force of gravity may play a role in further erosion, causing loose rocks and other materials to fall to lower levels. Gravity, of course, is the prime mover of materials in landslides, rockfalls, and similar phenomena.

Water running over the Earth's surface constitutes the chief agent of erosion. Running water serves not only to transport the products of erosion, but also to degrade the landscape further. The sediments and larger materials carried by a river or stream, for example, erode the banks and bed of the stream by collision, rubbing, grinding, and scouring action. This erosion results in a gradual widening and deepening of the channel. Eventually, the sediments and other materials carried by the stream are deposited.

Glacier ice moving through mountain valleys is a tremendous cause of erosion. Especially in the deepest part of the mass the ice picks up pieces of rock that, although moved slowly, scrape against the rocks of the glacial bed and destroy them.

Ocean waves and, in some cases, ocean currents and tides, produce intense erosion. All the high coasts are subject to destruction by the ocean waters; little by little, the rocks of these coasts are reduced to tiny fragments that are carried off to cover the continental shelves. The ocean waters, like the waters of streams and rivers, have an erosive (abrasive) effect due to the solid particles they carry in suspension.

The erosion of the Earth's crust, then, is effected through the work of numerous physical agents. It may also be effected, to a lesser degree, by vegetation and wildlife, and to a greater degree, by people. The roots of trees and other plants can exert great pressure on rocks, causing them to fracture and fragment. Burrowing, rooting, and climbing animals may also contribute to the destruction of rocks. Most important, people directly or indirectly may effect great destruction of the landscape. This destruction results principally from ignorance, carelessness, and thoughtlessness. On the other hand, human knowledge, care, and planning can protect much of the land from needless or unwelcome erosion. Conservation has gained support throughout the world.

ICE—An extremely important agent of erosion is glacial ice, which, moving slowly along the sides of mountains like a gigantic river, carries away masses of rock; these in turn scrape against the ground, eroding it and changing the landscape.

ROCK AND THE SEA—This rock rising in solitude from the middle of the sea bears witness to the erosive power of the sea and its currents. Along high coasts the sea causes deposition of sediments on the continental shelves.

THERMAL EROSION | the physical weathering of rocks

Erosion of the Earth's rocky crust is produced by the action of various agents, including heat, water, ice, wind, and gravity. The form the landscape assumes after erosion depends not only on the main agent of erosion, but also on the mechanical and chemical properties of the rocks themselves and on the ways in which they have been formed and changed by orogeny and other evolutionary phenomena. This article discusses the way in which thermal erosion occurs. Thermal erosion is produced in rocks by the absorption and radiation of solar heat in the alternating periods of day and night, and by the alternate freezing and thawing activities during the coldest periods of the day or the year.

THE HEAT THAT STRIKES THE ROCKS

The surface of the Earth is subject to intense radiation from the sun. The solar heat produces disintegration of the rocks—a disintegration proportionate to the difference in temperature on the surface of the rock between the hours of most intense radiation and the hours of the middle of the night. The surface of the heated rock receives most of its heat directly from the sun, not from the air surrounding the rock. As a matter of fact, the air derives its heat principally from the rocks themselves, rather than from the sun.

The disintegration of the rocks is brought about by their continual changes in size as a result of continual changes in temperature. As rocks absorb heat energy, they expand; as they radiate or lose heat (as they cool), they contract. This alternating expansion and contraction produce fissures in the rocks—the beginning of the disintegration process.

The rate of disintegration is proportional to the abruptness of the temperature changes to which the rocks are subjected. In other words, if the difference between daytime and nighttime temperature is slight, disintegration proceeds very slowly. However, if the temperature rises rapidly when the sun comes up and if it drops sharply when the sun sets, disintegration proceeds at a very rapid pace. The latter conditions apply where the atmosphere is clear and the sun approaches the zenith—on high mountains, in tropical regions, and in deserts. Anyone who has been on a mountain knows how quickly the temperature drops when a cloud blocks out the sunlight for even a short period of time. Indeed, even the passage of a single cloud can accelerate the disintegration of rock on a mountain.

In desert climates the atmosphere is almost always free of clouds, and the action of the sunlight is analogous to that on high mountains. Because of the greater density of the atmosphere and the higher temperatures, the thermal variation (the variation in temperature from maximum to minimum or vice versa) is only slightly less in the desert than it is in the mountains. As is commonly noted, at the rising and setting of the sun in the deserts, the temperature changes very quickly. It is not at all unusual for desert temperatures to drop 50° F after the sun sets.

In polar regions, on the other hand (given the duration of the day and the night), the temperature remains virtually unchanged for months; and thus the effects of solar radiation are less destructive than in the mountains and deserts. However, a general rule still holds: in whatever climate thermal erosion occurs, it proceeds faster and more effectively at high elevations than at sea level. Although desert landscapes are shaped by wind and by rock fragmentation due to wide temperature fluctuation, greater influences are erosion and flash floods.

THERMAL EROSION—The disintegration of rocks is due to continuously alternating expansion and contraction. Exposed to the intense radiation of the sun, the rocks expand; then, when the curtain of night descends, the rocks lose their heat and contract. This mountain, little by little, seems to be literally crumbling away to become one with the desert sand at its base.

THE MECHANICS OF THERMAL EROSION

As previously noted, the temperature variations to which rocks are subjected result in the formation of fissures that eventually break up the rock. This mechanism would be effective even if the rock were as perfectly homogeneous and compact as a block of glass; but in reality rocks possess properties that enable heat to act more effectively than it would on glass or a homogeneous material.

Igneous rocks (created by the solidification of magma) and metamorphic rocks (those altered by forces that have caused recrystallization) are composed of granules of different materials joined together. Inasmuch as these various components expand at different rates, they are easily separated from one another by changing temperatures. For example, granite consists of quartz, feldspar, mica, and other minerals. The quartz expands less than the feldspar and mica; therefore, a drop in temperature causes the feldspar and mica granules to separate from the granules of quartz.

Even sedimentary rocks have a tendency to break up, or, more precisely, to foliate along the surfaces parallel to the layers of sedimentation. Variations in temperature naturally increase the splits between one stratum and another, causing them to separate in time.

FREEZING ACTION

By freezing action is meant explicitly the freezing of water within the fissures of a rock. One can gain an appreciation of what happens when water freezes by conducting this simple experiment: fill a glass bottle to the top with water, seal the top, place the bottle in a strong paper bag (for protection) and put the bag and bottle into the freezing compartment of a refrigerator. On removing the bag from the freezer after several hours, the experimenter will find that the bottle has been broken. When water freezes, it increases in volume about 9 percent and, therefore, exerts a great force or pressure on the sides of its container. The pressure exerted by the expansion of freezing water is great enough to burst even thick metal tubing. In fact, the pressure is greater than 100 kg/cm^2 (about 1,400 lbs/in.^{2}); thus, on a surface no larger than the palm of a hand the expansion of freezing water exerts a force of about 10 tons. No rock can resist such great force, and so it splits.

Although this weathering action is slow at first, it continues irresistibly. If even a minute quantity of water seeps between the granules of a volcanic rock or between the strata of a sedimentary rock and freezes there, in a short while the size of the crack will increase.

Later the ice melts, and still more water enters the widened crack to freeze during the next cold period, widening the crack still more. Thus, slowly, a piece of the rock is broken away; at the same time, the remaining mass is attacked again to be further broken up. Obviously the speed and effectiveness of this freezing and thawing action depend on the frequency with which the surface of the rock is heated and cooled.

THE EFFECTS OF THERMAL EROSION

To see the effects produced by a single type of erosion mechanism, it is necessary to find a location where that mechanism alone has been acting. For example, thermal erosion may be readily observed in the desert, where heat acts almost exclusively and other erosive agents have only secondary importance. On high mountains, and especially in wet and cold climates, the effects of thermal erosion are cloaked, especially by the effects of running water and ice.

In general, thermal erosion produces rounded forms, which can be seen both in the rocks that have suffered erosion and in the fragments that have broken from them. The mountains of the Sahara provide a clear indication of the speed and intensity of thermal erosion. In an age not too remote, a few tens of thousands of years ago, the Sahara had a wet climate; it was covered with vegetation, and its plains, now completely arid, were fed by streams that flowed down from mountains, leaving their traces in mountain stream beds and valleys.

When the climate had become arid, the principal agent of erosion left at work was the heat of the sun. This agent has worked with tremendous effect: in just a few millennia it has gnawed at the sides of the mountains, sending rounded pebbles and boulders tumbling to their bases.

Even more obvious—also because of the rapid action that produces them—are the effects of freezing and thawing. Alpine climbers prefer to assault the vertical walls of a mountain during the coldest hours or, in any event, before the sunlight strikes the mountain walls. With the appearance of the sun the ice that has impregnated the numerous cracks in the rock melts, causing fragments to fall away, fragments that the ice had previously cemented together. This falling of stones is proof that freezing incessantly detaches pieces from the rocks; these pieces accumulate at the foot of the mountain, pulled down by the force of gravity. The fallen debris from the mountainside may continue to accumulate at the base of the mountain or it may be carried quickly away by other erosive agents, according to circumstances.

At the base of certain rock walls, such as those of the Dolomites, the fragments accumulate, forming immense gravel heaps; in the western Alps, where the walls are steeper and the valleys narrower, the debris falls into the beds of rushing streams and is carried far away. In general, where water, wind, and ice act as agents of transportation, accumulations are not formed at the base of the walls from which the debris is broken off.

EOLIAN AND CHEMICAL EROSION | wind, sand, and gas

1

← **A CAVERN IN CALCAREOUS ROCK**—Caverns in calcareous and dolomitic rocks are created by the solvent action of water that, having absorbed carbon dioxide from the soil, has then carried away the calcium and magnesium carbonates.

Water rich in carbon dioxide also has a strong solvent action on rocks composed of silicate sands (or other material that is resistant to the action of water) where these are cemented together by calcium carbonate. A lowering of the water temperature or the loss of the dissolved carbon dioxide then causes precipitation of the calcium and eventually the creation of stalactite and stalagmite formations (Illustration 1).

The forces of nature work unceasingly to alter the appearance of the Earth. These forces attack the landscape in many ways. For example, air erodes rocks by both chemical and mechanical action. Mechanical erosion takes place when sand and dust particles are blown against the rock. Chemical erosion is caused by certain gaseous components of the air that, alone or dissolved in water, may react chemically with the mineral components of the rock, or may simply dissolve them.

The action of atmospheric agents varies with circumstances, but it is always quite powerful. The effects depend on such factors as the intensity of the winds, the concentration of the various components of the atmosphere, and the type of rock on which they act. It is characteristic of atmospheric chemical action to cause chemical transformation of rocks—sometimes to the extent of destroying them—without directly carrying away the altered material. On the other hand, the mechanical action of the wind carries away eroded material as it is stripped from the rocks. These actions combine to produce constant changes on the Earth's surface.

THE CHEMICAL ACTION OF AIR ON ROCKS

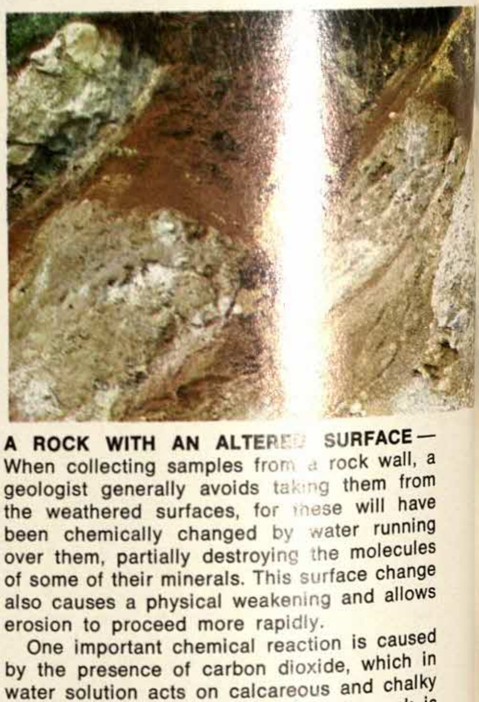
Atmospheric chemical action affects the surface stratum of rocks to a greater or lesser depth according to the permeability of the rocks themselves. The extent of the erosive action also depends on the climate in which it occurs. An Egyptian obelisk, taken from the arid climate of Luxor where it had remained in excellent condition for thousands of years, was substantially affected by atmospheric agents in just a few years after being placed in New York City; it became necessary to isolate it from the atmosphere to prevent its complete destruction.

Chemical erosion of rocks opens the way to other types of erosion. Water infiltrates and freezes, breaking away fragments of the rock. Channels are created for running water, which accelerates the erosion of the rock. The erosive effects take many forms, because the active com-

2

A PROCESS OF CHEMICAL CHANGE—This illustration shows the final result of the transformation of a rock into kaolin. Water has attacked some of the mineral components of the rock, changing them into a white colloid, kaolin (china clay). The kaolin has been carried away by the fast-moving stream to be deposited where the current slows on entering a valley. The kaolin used in the manufacture of ceramics is produced by a similar treatment of rocks. The formation of kaolin from rocks, when it takes place in great volume, produces a considerable increase in temperature; in some Grecian caves the kaolin is hot when it is extracted. The water, to which the kaolin is such easy prey, sometimes carries it great distances, leaving such materials in easily worked deposits.

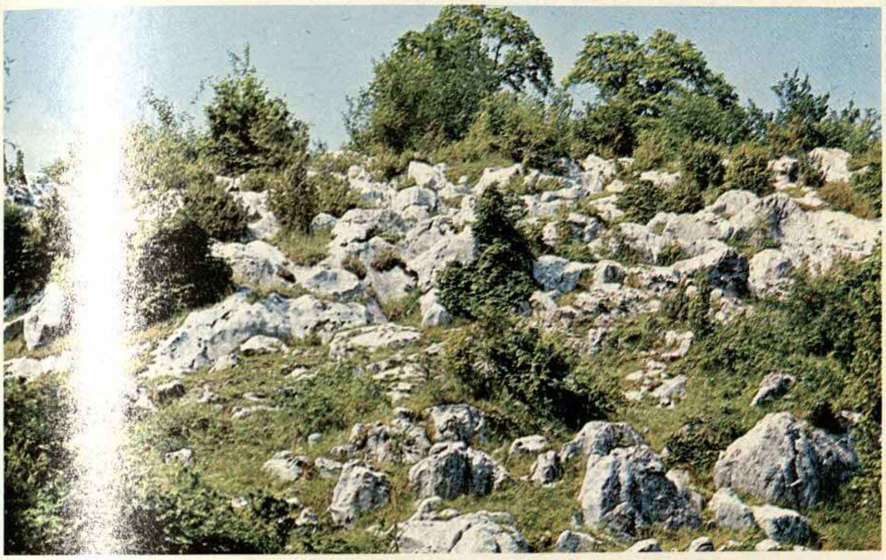
3



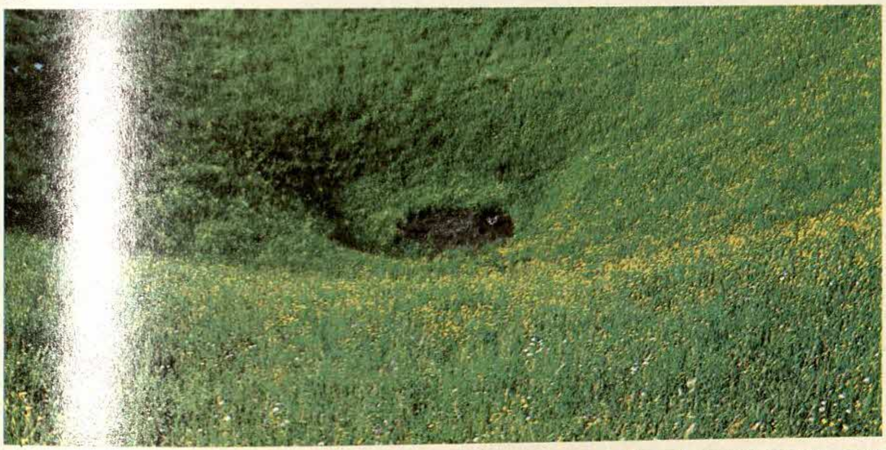
A ROCK WITH AN ALTERED SURFACE—When collecting samples from a rock wall, a geologist generally avoids taking them from the weathered surfaces, for these will have been chemically changed by water running over them, partially destroying the molecules of some of their minerals. This surface change also causes a physical weakening and allows erosion to proceed more rapidly.

One important chemical reaction is caused by the presence of carbon dioxide, which in water solution acts on calcareous and chalky rocks. The calcium carbonate of the rock is soluble in water, but only to a very slight degree—about 0.03 parts per thousand, by weight. However, if the water contains dissolved carbon dioxide, thus forming carbonic acid, it dissolves the calcium in the much greater proportion of 1.3 parts per thousand. If, in addition, the water temperature rises above 15° C, its solvent power is further increased. This solvent action of water acts on rocks composed of calcium or significant proportions of calcium, carrying away the surface stratum. When cracks occur, the water invades and enlarges the cracks. This phenomenon can easily excavate caverns, some of considerable size, in rock.

4a



4b



THE ACTION OF WATER ON LIMESTONE—Water, falling on this calcareous terrain and having absorbed carbon dioxide, has penetrated and enlarged the fissures of the bedrock (illustration 4a). Illustration 4b shows how the point at which the water entered has widened, creating a sinkhole. Depressions like this are common in calcareous terrain, such as the karst topography of central Tennessee and Kentucky. In conjunction with sinkholes, close and intricate networks of caverns are opened in the bedrock, complete with underground rivers and even underground lakes.

ponents of the air—water vapor, carbon dioxide, and oxygen—act in completely different ways in attacking the various mineral components of rocks.

Chemical action produces great changes on the silicates. Volcanic rocks, for example, are made up of a high percentage of silicates (feldspar), whose formula is fairly complex. Water condensing on the surface of rocks containing these minerals dissociates into the ions H^+ and OH^-. These ions transform the rock into two types of compounds, some soluble and some insoluble, that are precipitated in a colloidal form of clay. In this way, the rock is slowly changed into an argillaceous colloid—a great alteration caused by the chemicals in the air.

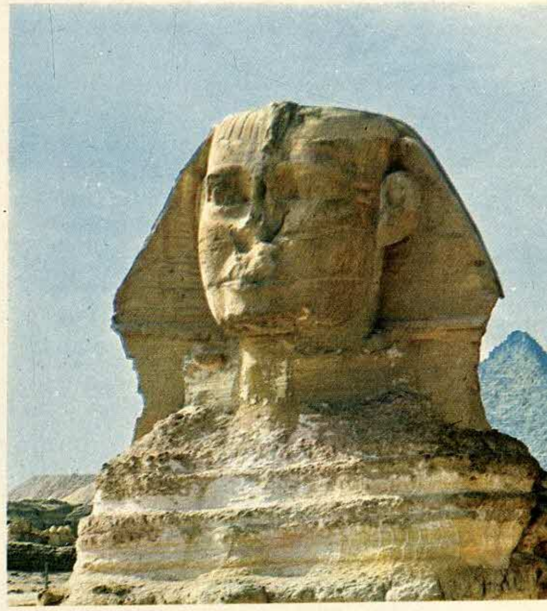
EOLIAN EROSION

Wind that carries particles of sand in suspension has a strong erosive effect on rocks it blows against; the sand slowly eats away the rock surfaces.

Certain conditions must be present for this type of erosion to take place. First, wind can pick up sand from the soil only where there is no vegetation or where the soil is very dry, as in the deserts. Second, the wind must be quite strong. A moderate wind will not hold the minute particles of sand in suspension, and the erosive action will at least be lessened, both because of the smaller quantity of abrasive material thrown against the rock and the lower velocity with which it strikes.

THE SPHINX—Many of the sandstone monuments built by the ancient Egyptians bear the signs of eolian erosion; typical is the Great Sphinx.

5



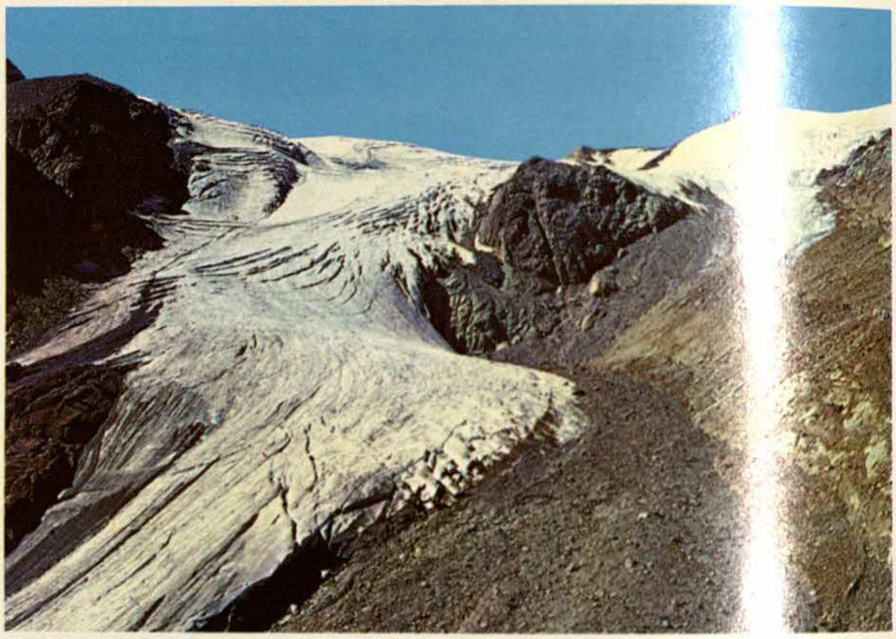
Eolian erosion acts only near the ground. Exceptionally strong winds may blow sand to greater heights, but most of the erosive effect results from those grains of sand closest to the ground. Another characteristic of eolian erosion is that its effect depends on the hardness of the exposed rock. Hard rocks resist such erosion to a great degree, while soft rocks are easily eaten away.

Still another characteristic of eolian erosion is that it forms prominent solitary rocks into aerodynamic shapes. This is especially true where the wind maintains a constant direction.

Finally, eolian action carries away the eroded material in the form of minute particles; the quantity of these is very small in comparison with the quantity of sand needed to effect the erosion.

GLACIERS | the beauty and power of moving ice

Glaciers—mighty masses of ice combining spectacular beauty with awesome power —have exercised a profound effect on the appearance of the Earth. Although not the principal agent of erosion (that distinction belongs to the rainwater that erodes the soil), glaciers have been the strongest determining factor in shaping many regions, particularly those with colder climates. The entire Alpine range, for one example, shows signs of tremendous glacial erosion that has occurred several times during the past million years. To understand the erosive action of glaciers, their structure should first be studied.



WHERE GLACIERS ARE FORMED—In this declivity on one of the slopes of the Jungfrau, the formation of a large glacier can be traced. The winding flow shows how glaciers adapt themselves to the various obstacles in their paths. Originating in a feeder basin (not seen in the photograph), the glacier flows down the valley slope by a route that avoids the spurs of the harder, less erodible rocks jutting from the floor of the valley.

When the valley glacier is forced to change direction or to move faster, it may not be able to change its shape in time. Then the ice breaks up, and cracks or crevasses are formed in the glacial mass; the crevasses vary in form according to the direction of the movement of the ice. The Alpine glaciers move at a speed of a few meters a year; glaciers covering Greenland and Antarctica flow more than a meter a day.

PRECIPITATION AT HIGH ALTITUDES—As altitude increases, the amount of rain and, if the temperature is low enough, snow increases. These mountain huts near Grindelwald, Switzerland, seen at the top of the photograph, are almost completely covered by snow; but their very presence indicates that they are located below the permanent snow line.

THE PERMANENT SNOW LINE

It is a meteorological principle that the amount of precipitation (the fall of rain or snow) increases as the altitude increases. Experiments have been conducted with rain gauges adapted to measuring snowfall, set up in several locations of a given mountainous region, from the valleys up to the mountain summits. After a year, the gauges at higher altitudes invariably collect more water than those at lower altitudes. It is also true that, as altitude increases, temperature decreases, and the annual period of snowfall becomes longer.

Thus, there are two reasons for a greater snowfall at higher altitudes: the total amount of precipitation is greater, and more of this precipitation falls in the form of snow. Above a certain altitude, called the permanent snow line, all the precipitation that falls throughout the year is in the form of snow. This does not mean that the ground above this line is always covered with snow, for the heat of the sun is also a determining factor. In the Alps, the permanent snow line is at about 2,900 m (about 9,500 ft); most of the snow falls during the winter. The illustration (left) shows a village of mountain huts near Grindelwald, Switzerland, buried under the snow; this village is located about 1,000 m (about 3,200 ft) below the permanent snow line.

HOW A GLACIER IS FORMED

An important phenomenon occurs far above the permanent snow line: the amount of snow that the sun is able to melt in a year is considerably less than the amount that falls and accumulates on the ground.

If nothing occurred to compensate for

this accumulation, a mountain would soon be completely covered with snow and its height would continue to increase. However, several things do occur. Snow in the lower layers of the accumulation diminishes considerably in volume, and then changes into ice. There are several reasons for this. First, the snow is compressed by the layers of snow above, and is thus made more dense. Then, during the warmer season, part of the surface snow is melted, and some of the water seeps down to the compacted lower layers. When this water freezes, the sodden snow becomes ice. In the coldest climates, the formation of ice is caused solely by the pressure of the upper layers.

The ice does not continue to build up because of a simple phenomenon known as "refreezing." Freezing water increases in volume, but very great pressure (applied in this case by the upper layers of snow) will force the ice to occupy less space by melting at a temperature below 0° C (32° F). In its liquid state, the water can flow away from the area of compression; once free of the pressure, however, it immediately refreezes because of its low temperature. Thus the ice, adapting to the forces acting on it, changes its shape.

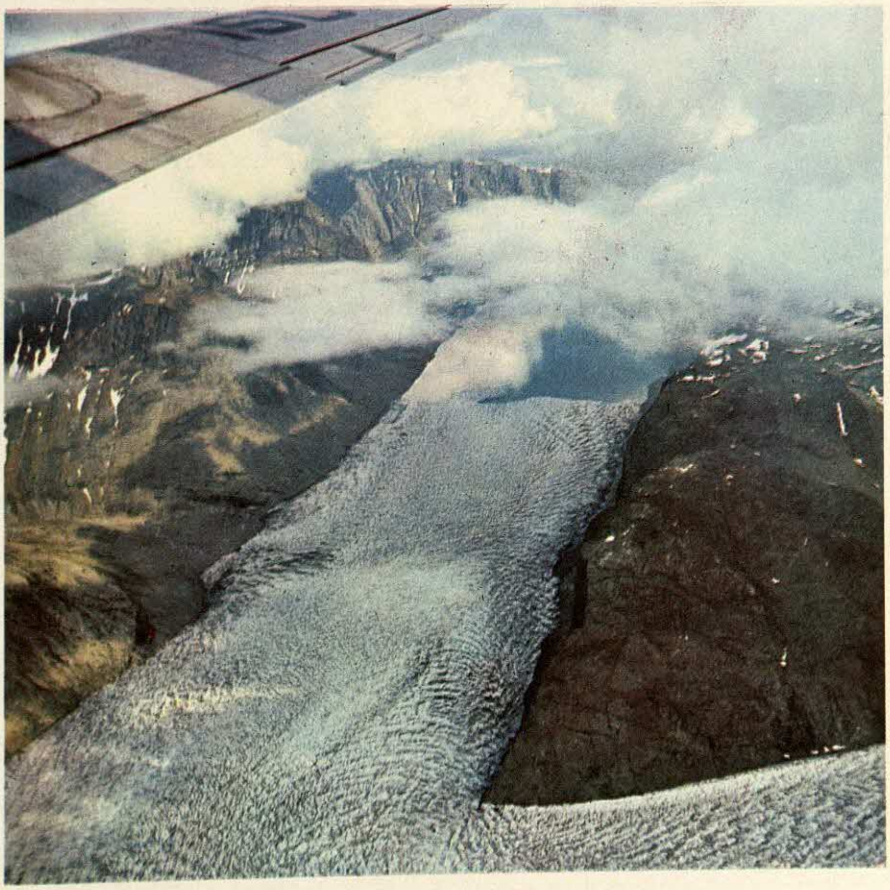
THE GREENLAND GLACIER CAP — Greenland is completely covered by an enormous glacier. The snow that falls on this huge island must travel thousands of kilometers to reach the sea. Thus the glacier has attained a thickness of over 1,000 m (over 3,200 ft) and even up to 3,000 m in some places. This great layer of ice could, according to the isostatic principle, force the island beneath sea level, and it probably does so over large areas.

The ice that accumulates on the high mountains is forced by its own weight against the ground that supports it. This force is sufficient to move the ice down to the lower areas and carve out the valley through which it flows.

Thus the ice moves from the highest parts of the mountain range where it was formed and, gathering mass, runs along the floor of the valley it has excavated until it reaches altitudes well below the permanent snow line. Below these altitudes, the surface of the ice collects less snow than the ice is able to melt in the course of the year; and so the ice itself must melt. This diminishing process continues until the amount of ice furnished by the mass coming from above and by snowfall is equal to that which the sun is able to melt.

This is a glacier—a slow river of ice flowing down a slope. In the Bernese Oberland of Switzerland, one glacier has descended to less than 1,000 m (over 3,200 ft). In very cold regions, glaciers can descend as far as the sea.

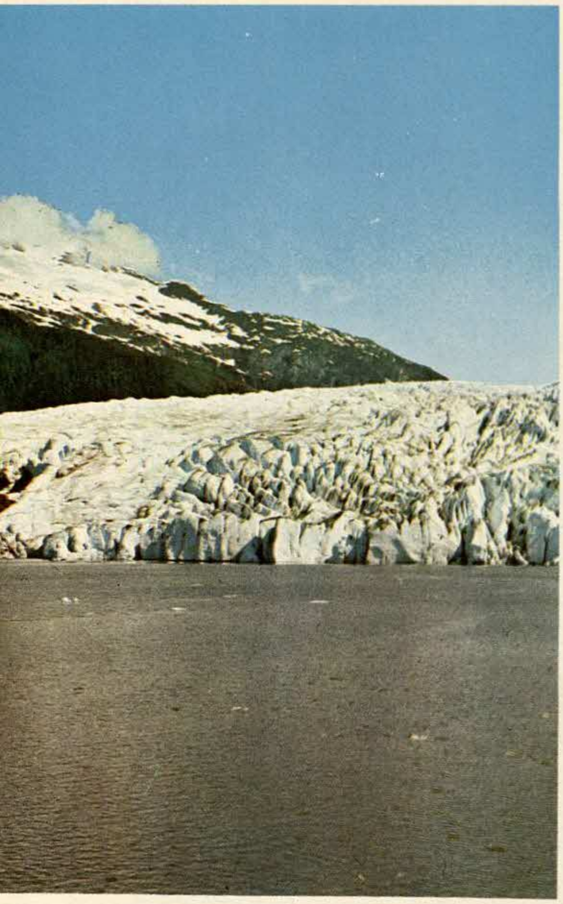
THE CONFLUENCE OF GLACIERS—As happens with rivers, the immense currents of two glaciers may flow together, creating a still larger glacier. This phenomenon is especially common in the regions of Antarctica, Greenland, and Alaska where there are boundless extensions of the ice masses. In the photograph, the tributary flow to the right joins the main flow of the glacier to form a huge V before emptying into the great fjord of Tunugdliarfik in Greenland, coming at the end of its course within sight of the sea. The colossal excavation of the fjord was caused by glacial erosion.



THE GLACIAL CLIMATES

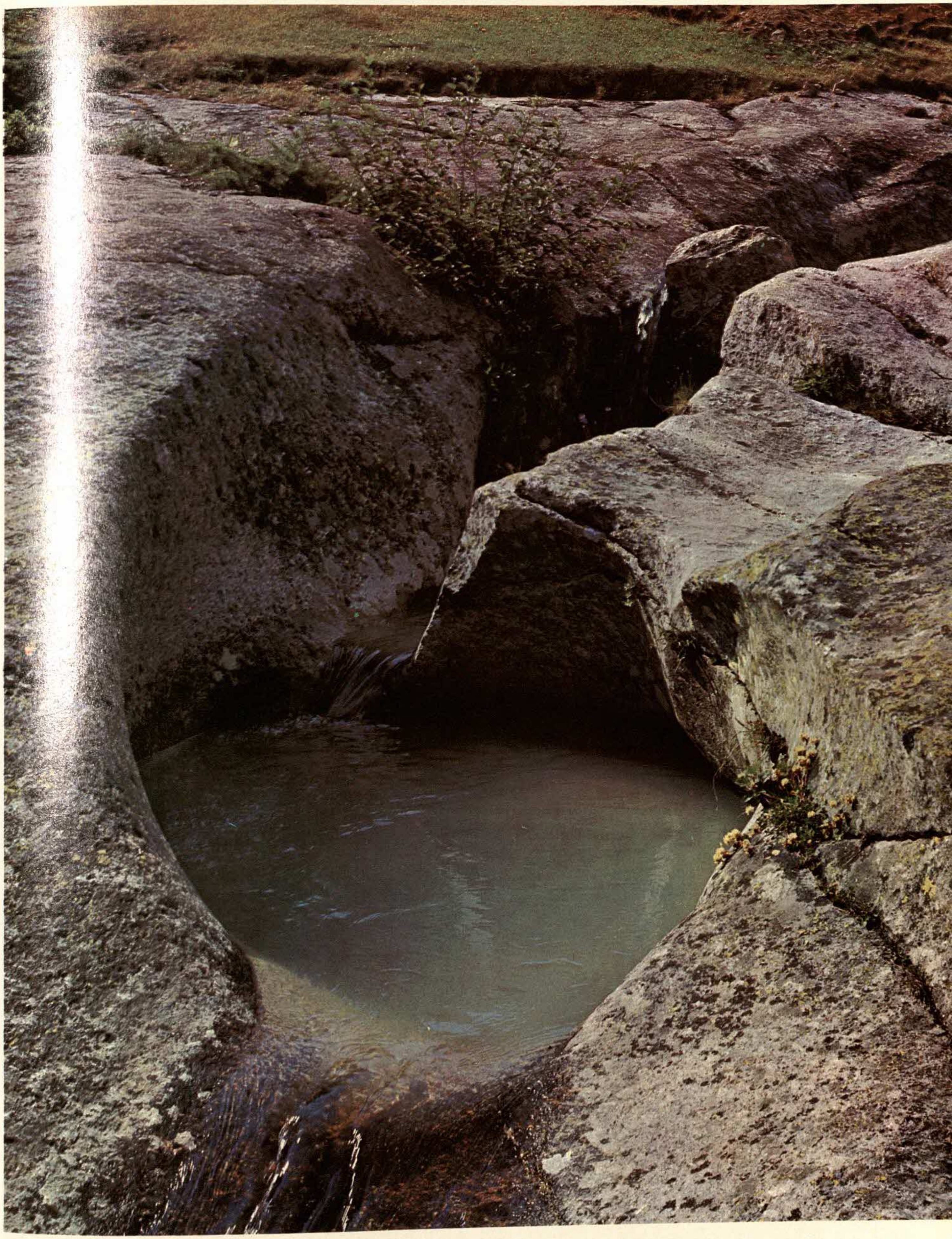
When the glacial ages were at their height, at least 28 percent of the land area was covered by glacial ice. More than 10 percent is now covered with ice, but it is in the higher latitudes. In order to determine the climate of the glacial age at coastal point A, for example, a point B on the same coast is located by finding the place where the present snow line has the same altitude as the glacial-age snow line of A. The present climate of B is then taken as representative of the former climate of A. Over a wide region, this method gives consistent results. Coastal points such as A are recognized to have had much greater precipitation than they do at present and to have had mean annual temperatures of 7° to 8° lower than now; in the interior regions, the increase in precipitation and decrease in temperature compared with present conditions were less pronounced. The subpolar climates, in other words, were shifted toward the equator during the glacial ages; and the shift may have amounted to as much as 15° of latitude for the northern belt. The pluvial conditions of the dry regions of middle and low latitudes support this conclusion because they seem to show that the middle-latitude belts of rain-bringing cyclonic storms shifted towards the equator. Evidence given by fossil animals in the northern hemisphere also indicates a southward shifting of the cold northern climatic zone through many degrees of latitude. Furthermore, the evidence of fossil plants and animals indicates that during the interglacial ages the climatic zones were shifted toward the poles and that at least once the zones in the northern hemisphere were pushed north of the positions that they now occupy. The climatic changes were world wide and contemporaneous; their causes have been studied by geologists, meteorologists, physicists, and astronomers. Although there is no proof that large fluctuations in solar energy have occurred, the assumption that they have done so is the hypothesis that seems to meet all requirements for the causes of the glacial climates.

A GLACIER THAT GOES DOWN TO THE SEA—At high latitudes, glaciers can flow right down to sea level, as does this one—the Mendenhall, near Juneau, Alaska. Once it has reached the sea, the glacier begins to float and, following the lines of the crevasses, great blocks break away from the mass to drift in the ocean. These blocks—icebergs, great mountains of ice—pose a great hazard to shipping. The icebergs of the North Atlantic come from the glaciers of Greenland; those of the south seas come from Antarctica.



A CAVITY IN AN ANTARCTIC GLACIER—In the huge glaciers that cover the Antarctic continent, slight detours imposed on the glacial flow by obstacles, or melting caused by solar heat, produce cavities that sometimes grow to grandiose proportions, as this photograph shows. Antarctica has a climate as dry as that of the Sahara, but because of the intense cold, a light snowfall is enough to produce accumulations of thousands of meters of ice. If this ice were suddenly to melt, it would raise the sea level all over the world by at least 50 m (about 165 ft), submerging most of the world's great coastal cities.

GLACIAL EROSION | abrasion on a mighty scale



← **A GLACIAL KETTLE**—This kettle-shaped excavation (Illustration 1) was formed by a falling stream following the surface melting of a glacier. Pouring into a crevasse, the stream stirred up the morainic rocks at the bottom, causing them to rotate and eventually grind out this hollow. Because of its shape and size, it is often called "the giant's kettle."

The action of mighty rivers of ice on the ground beneath them is tremendous. Glaciers deeply erode the beds through which they flow. The rate at which the erosion occurs varies, depending on the speed and mass of the glacier, its weight and the weight of the solid material it carries, and the relative hardness of this material and of the ground being scraped by it.

It is impossible to determine the depth of the bed beneath a glacier that is still standing, and it is equally impossible to determine how much time was required to produce the effects of erosion that can be observed once a glacier has retreated. However, where these phenomena are now in progress, detailed studies can be made.

RUBBLE ON THE SURFACE OF A GLACIER—The abrasive action of a glacier is produced by its own weight and the force it exerts on the rocks over which it flows, aided by various-sized particles of material that are the by-products of other forms of erosion. Numerous pieces of rock fall on top of the glacier and remain there for some time. The photograph shows a layer of such fragments deposited on the surface of a glacier.

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RUBBLE INSIDE THE GLACIER—With time, the glacier moves, and new snow covers the old surface rubble (as long as the glacier remains above the permanent snow line). The debris formerly on the surface is eventually imbedded in new ice; after several repetitions of this process, the debris is buried deep within the glacier. This photograph (Illustration 3) shows some of the strata of an Antarctic glacier. The ice, mixed with rubble, scrapes against the sides and floor of the valley surrounding the glacier, leaving characteristic striations on the exposed rock that will be visible after the glacier has moved away.

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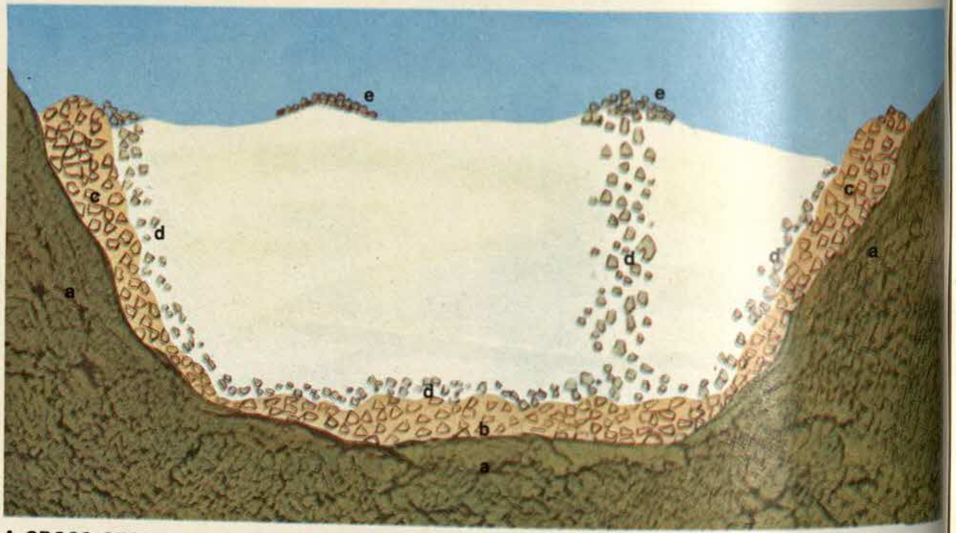
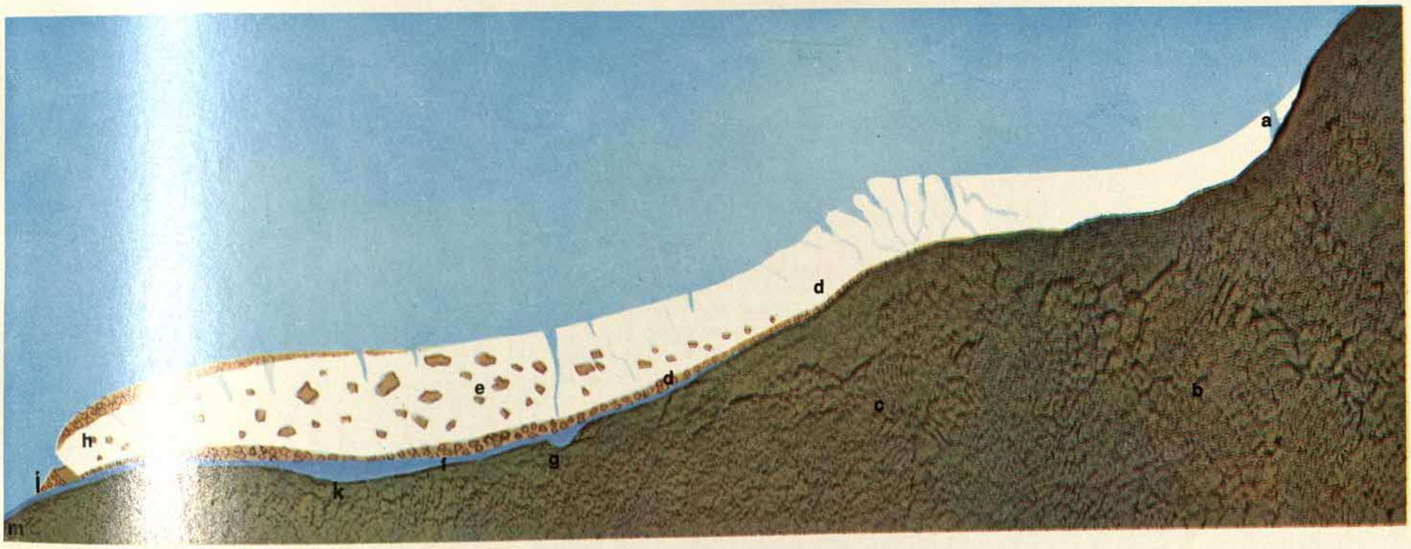


A CROSS SECTION—This section shows certain characteristics of a glacier that a longitudinal section would not show: **a** is the floor of the valley, composed of solid, compact rock; **b** is the ground moraine, the collected material that the glacier has deposited at the bottom or sole of the glacier; **c** are the lateral moraines, similar in structure to the bottom moraines; **d** are the englacial moraines, made up of rocky material torn from the walls of the bed, or material that has fallen onto the collecting basin from the mountainsides and sunk to become part of the internal mass of the ice; **e** are the floating moraines, material on the surface of the glacier, produced either by material falling on the glacier's surface (as on the left) or by fragments contained in the glacier that rise to the surface and are exposed by the melting of the surface layer (as shown on the right of the illustration).

A LONGITUDINAL SECTION—In this longitudinal section of a glacier, **a** is the terminal crevasse at the upper end of the collecting basin; **b** is a longitudinal section of the basin itself; **c** marks the first breaking-up point of the glacier, where the sharply pitched slope increases the speed of flow and changes the glacial direction considerably, causing the ice to become heavily crevassed; **d** is the bottom moraine, made up partly of rocks scraped away by the glacier and partly of rocks that have fallen onto the glacier and sunk to the bottom to deposit themselves on the bed; **e** is the medial moraine, the cordon of rocks carried off by the glacier in a longitudinal line; **f** is the stream of water that runs parallel to the glacier at its base, finding its route through the porosity of the morainic rocks at the bottom and wherever the glacier does not fit perfectly against the terrain; **g** is a glacial kettle, a cavity formed in the rock of the glacier's bed when water, melted from the glacier's surface, flows down through a crevasse to the bed, stirring the morainic rocks in a whirlpool motion so that they grind out a cylindrical hole in the bedrock; **h** is the glacial tongue, the lowest part of the glacier, almost completely covered with morainic rubble; **i** is the glacial tongue that sometimes ends in a sort of doorway formed by the rapid melting of the ice at the front of the glacier; **j** is the terminal moraine, the accumulation of rubble carried down by the glacier and deposited at the doorway; **k** is a hollow scraped out by the glacier as it flowed over its bed; often, if the glacier retreats, the hollow remains filled with water, forming a glacial lake; **m** is a stream of water fed by the gradual melting of the glacier.



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MORAINIC MATERIAL — When a river or stream deposits material along its bed, the material is accurately graded according to size; at one point there will be only large stones, at another only sand, and at still another only the finest silt. This is not the case with glaciers, which transport the material eroded by their own action and by the freezing action that crumbles the sides of the valleys through which the glaciers flow without separating the small particles from large pieces.

Sometimes, material in the ground moraine is separated according to size; this occurs because the material is partially carried by the stream of meltwater that runs along the bottom of the bed. The stones in the foreground of this photograph are from a laterally deposited moraine. They have sharp edges because they were detached by freezing from the parent rock to which they belonged, and because nothing was present to dull their edges in the glacier that carried them. When, later on, the rocks were caught up in the valley streams, some of the edges became rounded. Characteristic of the glacial action is the presence of fragments of all sizes.

GLACIAL VALLEYS | products of massive erosion

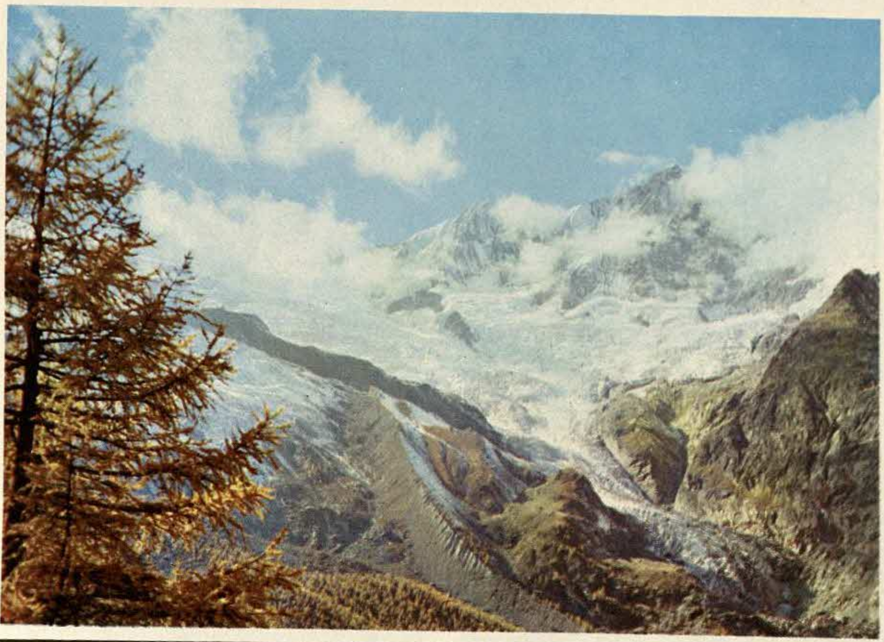
When man thinks about ice, it is usually in connection with wintertime sports or cold drinks. However, ice has played an enormous part in the formation of the world and, indeed, in the very appearance of man's earliest ancestors on the Earth.

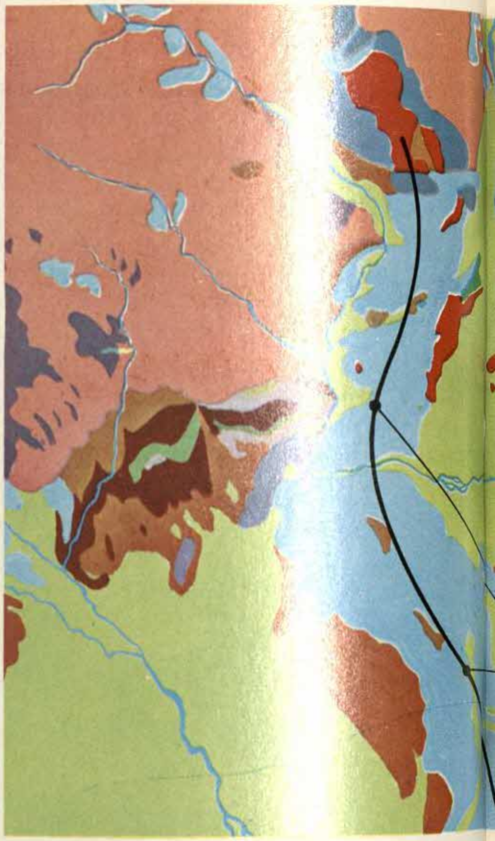
The study of glacial erosion is important for several reasons. In the first place, extensive land areas (Greenland, Antarctica) are still covered by glaciers that are shaping the soil beneath them. Second, regions of the Earth that today are free of glaciers, or only partially covered by glaciers, have been deeply carved by glacial erosion. This is the case in Scandinavia and the Alps, in Canada, and in other European and American regions. Finally, glaciers of remote ages greatly eroded the Earth's crust, and in retreating, left these regions flattened. The products of the erosive action of glaciers are visible today in the form of massive deposits and sediments laid down by glacial movements.

Glacial movement is extremely sensitive to climatic factors, although in ways that are not altogether understood. It is known that, in the past million years, the European glaciers have expanded five times, flowing down the mountains, and have retreated five times. Because the glaciers are now well in retreat, their powerful effects on the regions they invaded can be studied and understood with some perspective.

THE HISTORY OF A MORAINE—This glacier, of which only a small terminal tongue remains, was much more extensive a few centuries ago; it carried morainic material over a large area. Its bed is marked by the curved moraine in the center of the photograph, far from the present glacier; no new material is brought to it because of the glacier's retreat in recent years. The moraine is now subject only to the erosion of the water that gathers in the furrows running down from its crest. Meanwhile, trees have begun to grow on the moraine; if a thick forest should develop, erosion of the moraine would be considerably retarded. It would take millennia for the action of water to destroy a moraine of this size.

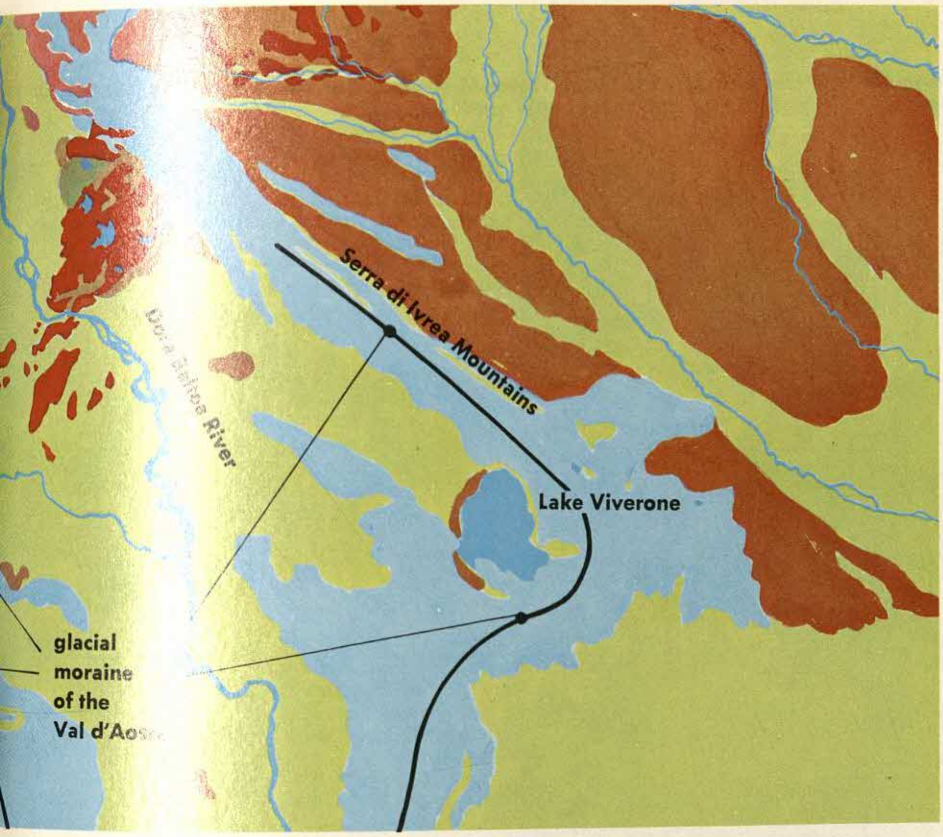
The glacier that builds a moraine can also destroy it. If this glacier had advanced instead of retreating, it would have acted like a giant bulldozer, pushing the moraine forward to where it would accumulate new material. However, the glacier is retreating, abandoning the moraine along its arc of maximum expansion. From the first moment of retreat, the slow decline of the moraine began.



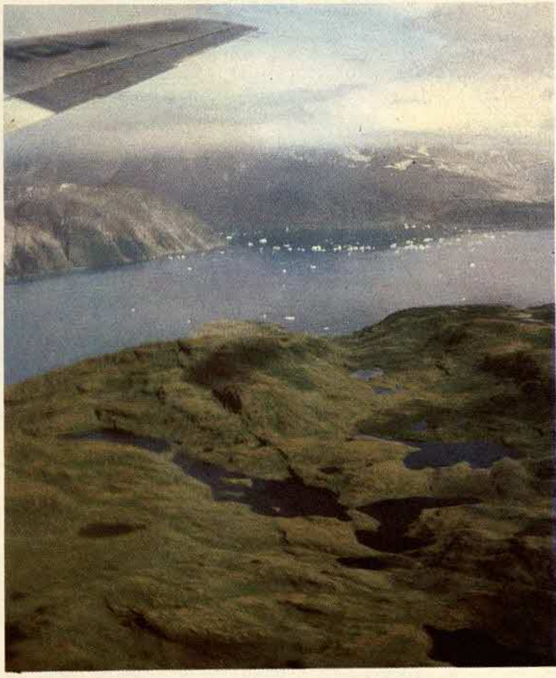


THE MORAINE OF THE VAL D'AOSTA GLACIER—During the glacial eras, the Val d'Aosta in northwestern Italy was invaded by a gigantic glacier that entirely filled it, leaving intact only the crests of the lateral mountains. This huge glacier, about 200 km (about 125 mi) long, was fed by glacial affluents from the main tributary valleys. Where the valley opens into the Po plain, the glacier built up an enormous moraine that still blocks the entrance to the valley. Its

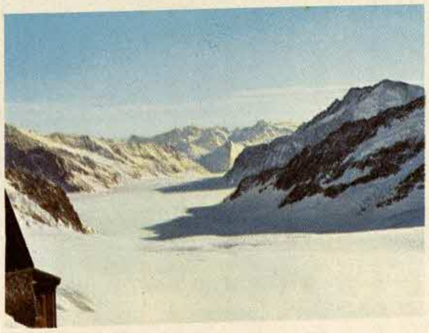
A GLACIAL VALLEY—The Loisach valley falls away from the Bavarian Alps to the German plain; it was cut by a glacier that today has melted away to a small field on the side of a mountain. At the time of its greatest expansion, the glacier filled the whole valley. Over thousands of years, a moraine built up where the valley opens onto the plain. There is much evidence of the glacier's former presence—the moraine at the mouth of the valley, the striations on the sides of the valley, and the valley's U shape. This shape is typical of valleys that have been cut by glaciers, unless they have been subsequently eroded by other elements that might change their shapes.



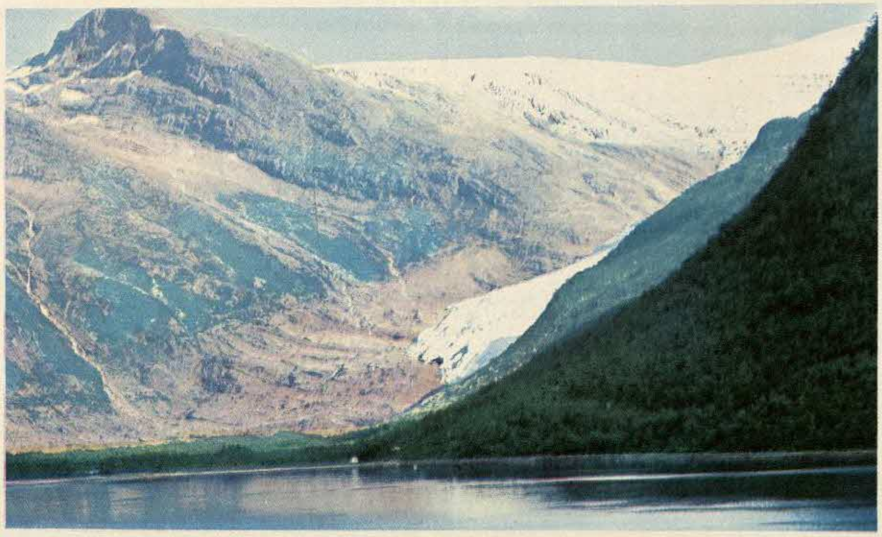
great width is due to the fact that the glacier, which had been restrained within the walls of the valley, spread out under its own weight as it flowed into the plain. To the east, the moraine ran straight, like a great wall, and built up a hill called the Serra di Ivrea. Moraines of equally imposing size were deposited at the mouths of many other valleys running down from the Alps—for example, the colossal moraines closing the south ends of the great lakes of the Po plain. The huge extent of the glacial erosion resulted in the filling in of a sea that, in the time preceding the quaternary glaciers (the Pliocene epoch), spread over what is now the Po plain. The sediments carried by glaciers and deposited on the bottom of the sea filled its depth of 100 m (about 300 ft) and continued to build up to its present level, which reaches 200 m (about 600 ft) at the foothills of the Alps and the Apennines.



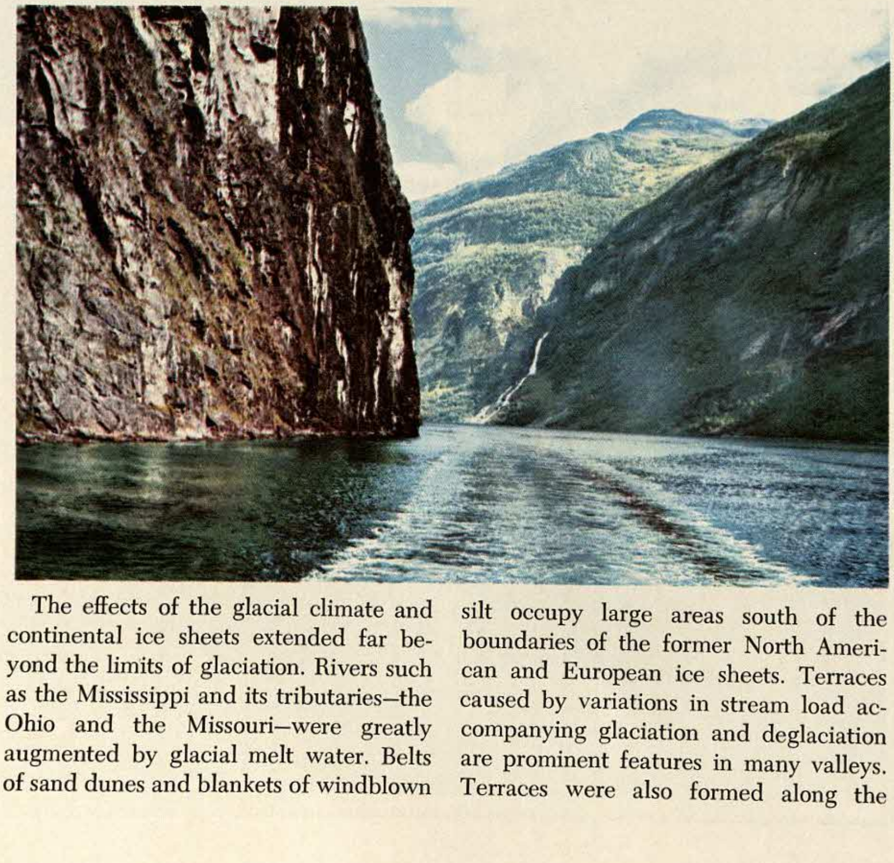
A CONTINENT CUT AWAY BY A GLACIER—During the Quaternary period, the glaciers reached their greatest penetration into regions of relatively warm climates, such as the Alps. In the colder northern regions, glaciers formed thick, continuous blankets over entire continents. The movements of these glaciers cut out very deep valleys in some areas, but their principal action was to flatten vast regions. This photograph shows a region of Greenland from which the glaciers have completely retreated; it is marked by rounded hills alternating with valleys in which water has collected to form a myriad of lakes. The thousands of lakes of this type in Sweden, Finland, and Canada have similar origins.



A VALLEY WITH THE REMAINS OF THE GLACIER THAT EXCAVATED IT—This valley falls away from the Jungfrau in Switzerland's Bernese Oberland. It was cut in the Quaternary period by a large glacier that has now retreated but has not disappeared. In fact, at 27 km (about 17 mi) in length, it is still the longest glacier in the Alps, and it still completely fills the glacial valley, which retains the characteristic U shape.



A FJORD AND THE GLACIER THAT CUT IT—The glaciers that covered the Scandinavian peninsula during the Quaternary period have now disappeared or greatly diminished, leaving behind the characteristic fjords they created in Norway. This photograph shows a fjord that still harbors in its valley the remains of the giant glacier that cut away the hard rocks of the mountains. Now the glacier is reduced to a small tongue that covers only a small part of the valley floor and stops short of the sea; at one time, however, the glacier not only reached the sea—it continued beneath the sea. Just as existing glaciers in Greenland and Antarctica extend into the sea, so did the Norwegian glaciers of a past era. After these glaciers retreated, the valleys extending down to the sea remained. The phenomenon is further complicated by the fact that some parts of the Norwegian coast have been slowly sinking; thus, the floors of some glacial valleys are now lower than when they were formed. Because of this, some fjords can be navigated safely by ships of fair size.



A DEEPLY CUT FJORD—The Geirangerfjord in Norway was so deeply cut out of the mountain rock that it is difficult to see its profile. Only the vertical sides of the fjord are apparent; the concave bottom is completely submerged. During the warm season, water from the glaciers that remain on the summits of the mountains flanking the fjord falls down the steep cliffs in picturesque cascades.

The effects of the glacial climate and continental ice sheets extended far beyond the limits of glaciation. Rivers such as the Mississippi and its tributaries—the Ohio and the Missouri—were greatly augmented by glacial melt water. Belts of sand dunes and blankets of windblown silt occupy large areas south of the boundaries of the former North American and European ice sheets. Terraces caused by variations in stream load accompanying glaciation and deglaciation are prominent features in many valleys. Terraces were also formed along the coast as a result of sea level fluctuations. In regions that are now arid, sizable lakes developed as a result of greater precipitation and less evaporation in glacial times; Great Salt Lake in Utah is a remnant of a much larger body that is known as glacial Lake Bonneville.

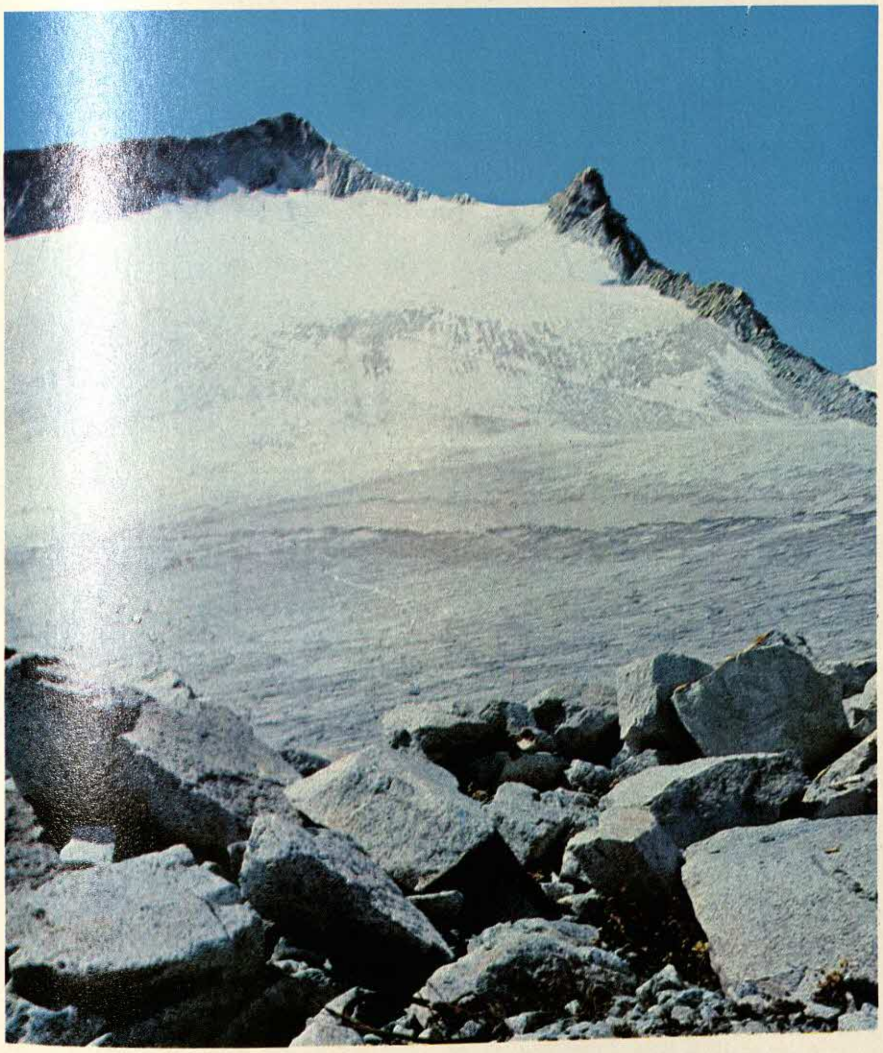
WATER EROSION | disintegration, transportation, and deposition

The chief agent eroding the Earth's crust is the water that runs over its surface in various forms. If it were not for orogenic phenomena—the processes of mountain formation—the action of this water would soon plane down the terrestrial formations of the Earth, reducing them to a height very little above sea level.

The quantity of water falling each year on the different regions of the Earth varies from place to place. In some parts of India more than 12 m (about 40 ft) of water fall each year—an average of one meter per month or about three centimeters per day. In regions where water is scarce the light rainfall does not amount to more than a few centimeters per year, on the average. Such is the case in the desert regions of the world.

The waters that fall on the Earth are destined finally to flow to the sea. A part evaporates, a part sinks into the ground, and a part flows over the surface of the land. The waters that evaporate have no effect on erosion except to cause surface changes on the rocks with which they come in contact.

The waters seeping into the ground likewise are of little importance in erosion, but they sometimes cause a weakening of the ground, thereby reducing its resistance to other agents of erosion. Actually, ground water aids in the for-

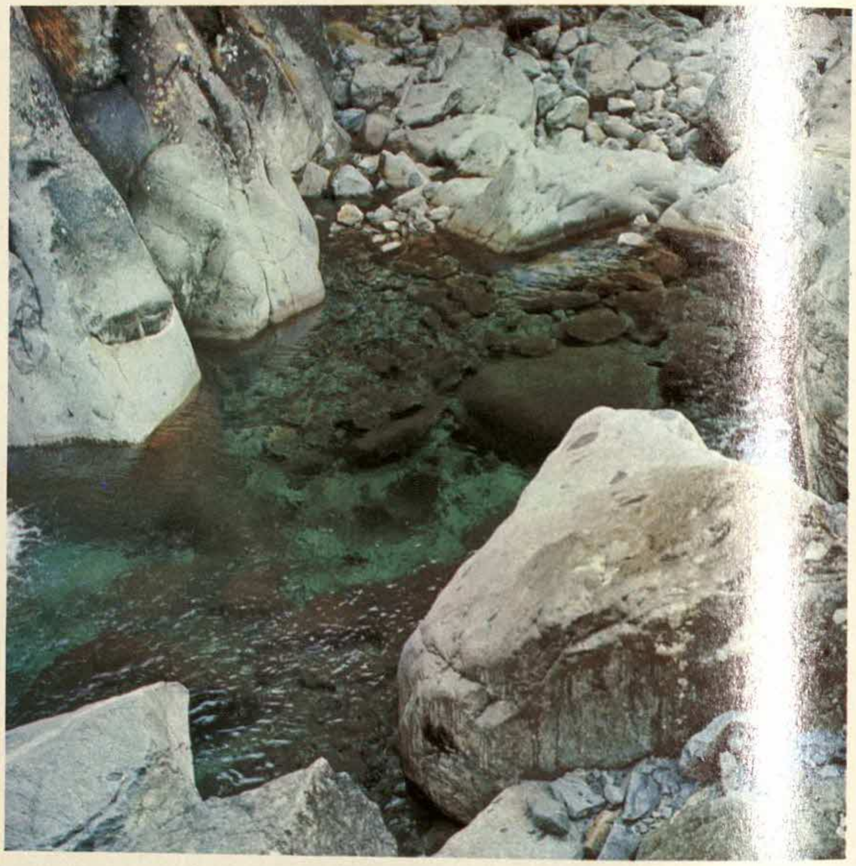


THE PHASES OF EROSION, TRANSPORTATION, AND DEPOSITION—Water causes erosion according to certain simple, basic rules. The first rule is that the force with which water acts is proportionate to the speed with which it flows. The speed with which water flows, in turn, is determined by many factors, but most importantly by the gradient of the bed in which it is flowing. Following a stream from its source to its mouth, one discovers that the erosive action of the water is greater closer to the mountain source. As the water flows onto the plain and nears the mouth of the stream, its speed decreases and, rather than eroding its bed and carrying the materials away, it begins to deposit the materials it had eroded earlier.

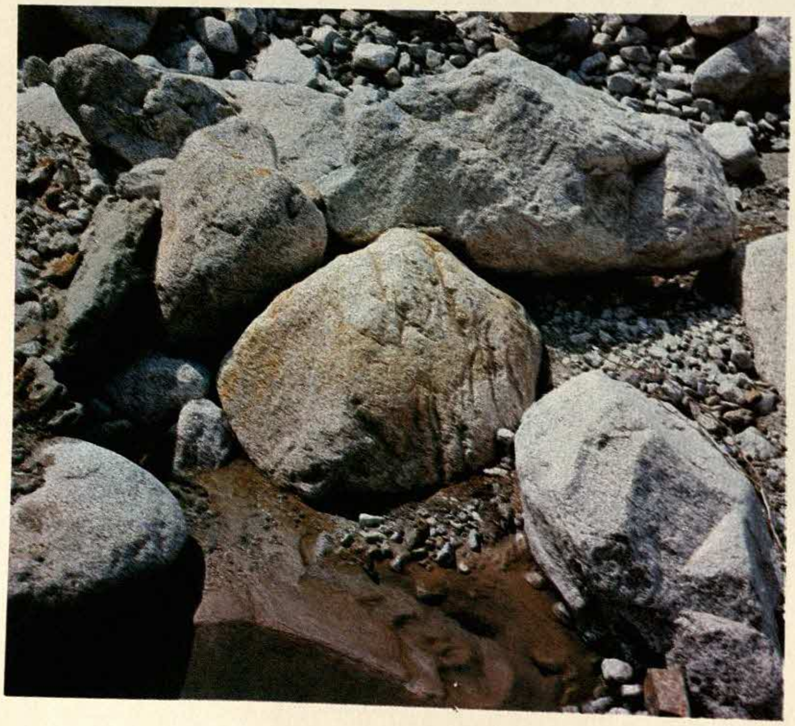
The volume of water carried by a stream also affects the speed with which that stream flows. Hence, a stream at flood stage has greater volume and flows faster than the same stream during a period of low water. Consequently, the stream in flood is a more effective agent of erosion. This fact leads to a second basic rule, which is that a given place in a stream bed may at times be eroded and at other times be built up by the deposition of sediments. Consider, for example, a stream coursing through plains country. When the stream carries very little water, it moves slowly and deposits the materials it has been transporting in suspension; on the other hand, when the stream is in flood, it flows with great speed, carrying away the materials it had formerly deposited.

Some streams begin their erosive work by carrying materials away from the mouth of a glacier. Here the fast-moving water picks up moraine material in large, sharp-edged blocks, such as those of the Adamello Mountain moraine shown in the photograph.

A SWIFT-FLOWING STREAM CUTS INTO A MOUNTAIN—The erosive action of a stream is very clearly shown in this photograph of the upper reaches of the Chiese River in Italy. The rocks carried by the stream are much more rounded than those still at the source; however, because of the steep slope of the bed, the water flows very rapidly and engages in very effective erosive activity. The sides of the stream bed have been heavily eroded; in fact, they have been cut away to some depth. The photograph, taken during a period when the water was low, shows very clearly those erosive effects that are largely masked by the water when it is at its average level.



ROUNDING OFF THE SHARP EDGES—A few kilometers away from the mouth of the glacier, the stones carried by the stream still show their edges, but these by now have been rounded by the abrasive action of the finer particles carried in the water and by rolling along the gravel bed of the stream. Where the gradient is very steep the rolling may be so violent that it not only wears away the edges of the rocks, but even breaks them into much smaller stones. This photograph shows rocks and stones from the Valcamonica River in Italy.



mation of rocks, in the consolidation of sediments, in the transformation of existing rocks, and in the formation of mineral deposits useful to the mining industries. Ground water moves so slowly that centuries may elapse from the time a particle of water is added to the ground water and the time it is discharged.

The waters that run over the surface of the ground, on the other hand, produce conspicuous erosion. Almost always, they flow on top of the ground for their entire journey back to the sea, but in some cases they run part of the way underground. The action of these waters in their voyage to the sea may be destructive or constructive. The action is constructive if the water deposits the materials it has carried in suspension or has pushed along before it.

The waters flowing over the surface of the Earth collect in courses that are known variously as brooks, creeks, rivers, and streams.

EROSION OF THE RIVERBEDS

evolution of the fluvial profile

The face of the land is sculptured by the agents of erosion, and the form of the eroded land depends on both the nature of the eroding force and the nature of the land. Formations consisting of hard, resistant rock are subject to only slight erosion; such formations are modeled into rounded shapes. Land made up of rocks that easily foliate into layers may contain a variety of formations, depending on the disposition and attitudes of the layers. It is impossible to formulate general rules to predict all the forms of erosion, but ordinarily it is easy to interpret the forms that appear and to predict how they will evolve.

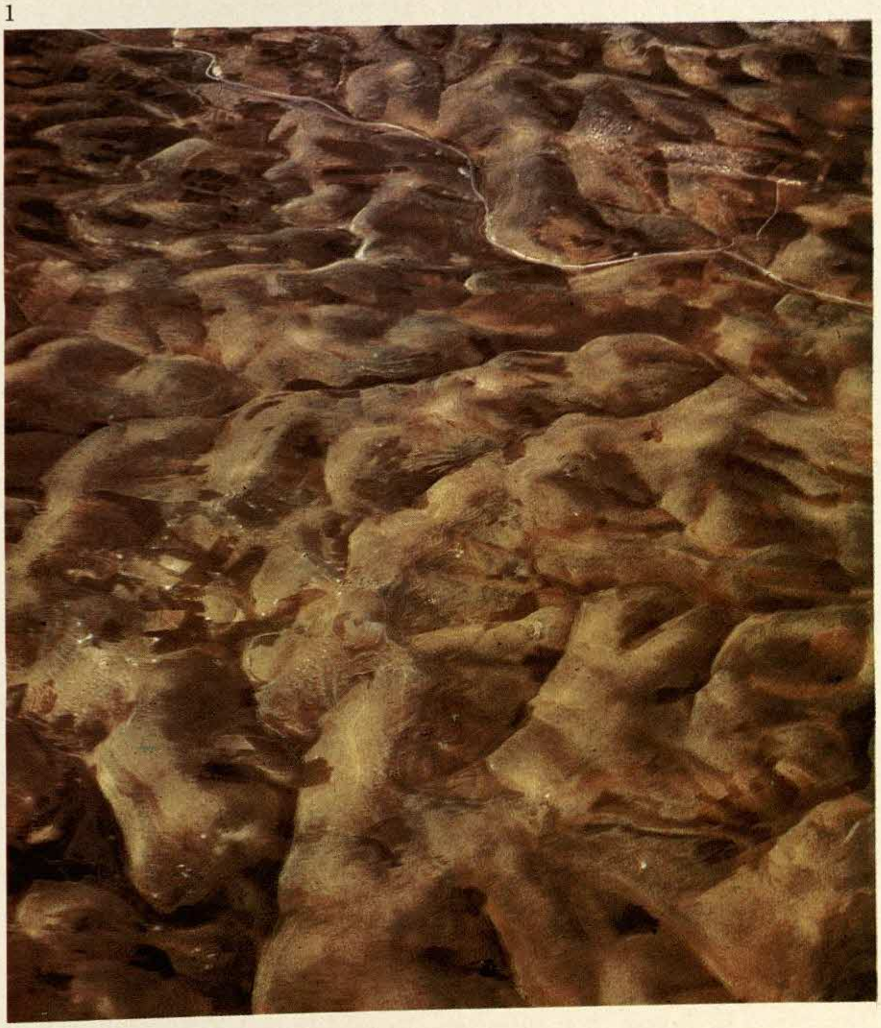
The study of the forms created by fluvial erosion is of the greatest importance because it provides clues as to the probable action of water in time and indications of how that action may affect men and their possessions. Men have good reason to live near rivers, not only because such watercourses still serve as avenues of transportation, but because their banks have become the sites of rich industrial cities that cannot be abandoned simply because they may be threatened by the rivers. In addition, successful crop cultivation is often dependent on river water for irrigation during seasons of sparse rainfall. However, even in this case, floodwaters that overflow the banks are to be feared, for they can destroy crops and, in the worst instances, the fertile land itself, thereby damaging the economies of entire areas.

The most effective way of mitigating floods is to reduce the peak of the flood by withdrawing some part of the natural discharge of the river—either by diverting the flow in a low-lying depression or by building a dam across the valley of the river and storing behind it a part of the flood discharge. The probability of flood levels and their incidence can be solved by mathematical statistics.

Knowledge of the ways in which rivers can be tamed and turned to the service of man is extremely important; such knowledge is obtained through a study of hydrology.

THE INTERWEAVING OF THE RIVER VALLEYS —This interweaving of valleys in the desert region near Amman, Jordan, proves that even in desert lands the forces of surface-water erosion are at work. Here, however, the effect is much less noticeable than in those regions where rainfall is abundant. A particularly interesting characteristic of this landscape is that all the valleys flow together in the direction of the largest valley—much as the branches of a tree converge on the trunk. The surface water erodes the land as it wends its way to the sea. There are no basins in the area; each valley descends unbroken at a greater or lesser incline toward lower land. All the mountainous regions of the Earth, viewed from the air, show this characteristic of valleys. In some regions, however, the rivers flow through valleys that were originally created by the erosive action of glaciers that occupied them in the past, when ice was carving new landscapes on the Earth.

1



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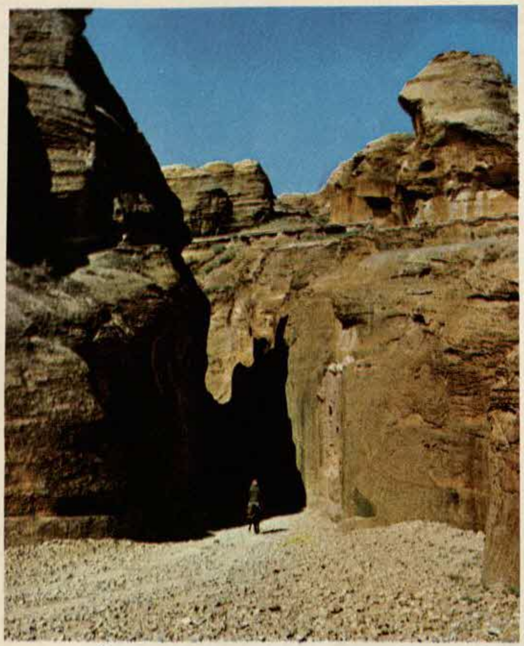
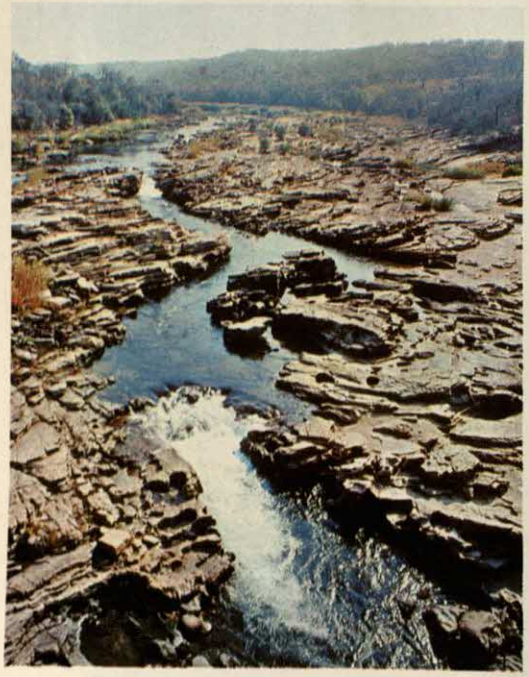


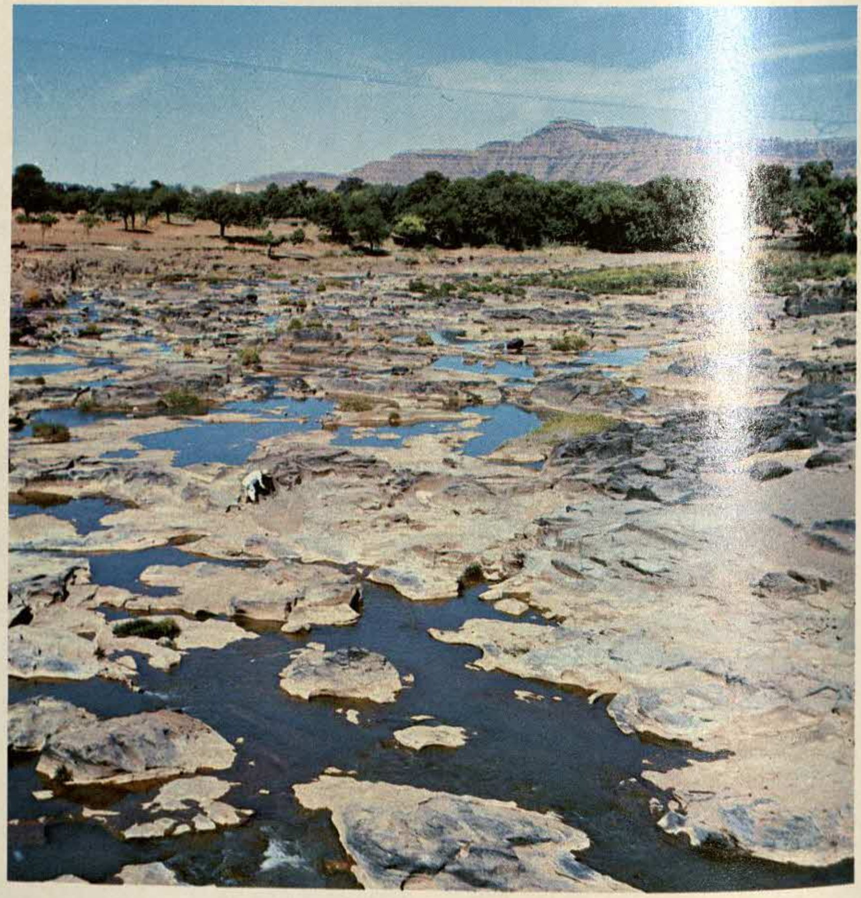
A RIVER GORGE—A watercourse—once violent, but now limited to rare flows of water from occasional rains—cut this deep gorge among the soft rocks near Petra in Jordan. The low resistance of the rocks allowed the water to cut a channel so rapidly that the vertical section remained uniform. On the bottom of the bed, now completely dry, are materials eroded from the mountains upstream.

TWO STREAM BEDS COMPOSED OF HARD HORIZONTAL ROCKS—A general rule of erosion states that ordinarily stratified rocks are eroded either parallel to the strata or perpendicular to them, rather than in a random way. These two streams (Illustrations 3a and 3b) confirm the rule: in both cases the water runs over rocks composed of strata that are horizontal or nearly so. The river in the Tete area of Mozambique (Illustration 3a) runs over slightly inclined rock strata. Where the water runs slowly over the surface of the rocks, it erodes only slightly. However, where the water flows most rapidly and when it has begun to erode the rocks at several points, it has cut a straight channel, similar to that cut in horizontal rock layers by the Colorado River. This does not mean, of course, that erosion occurs only in the cut made by the stream; along the entire surface where water flows, fragments of rock have been broken off from the underlying strata and carried off by the water. The flat riverbed is deepened, but its shape is not altered. The Kistna River in India (Illustration 3b) also flows among resistant rocks and slowly cuts a bed that, during periods of low water, is divided into rivulets. Because the river is well above sea level, erosion takes place rapidly.

3a

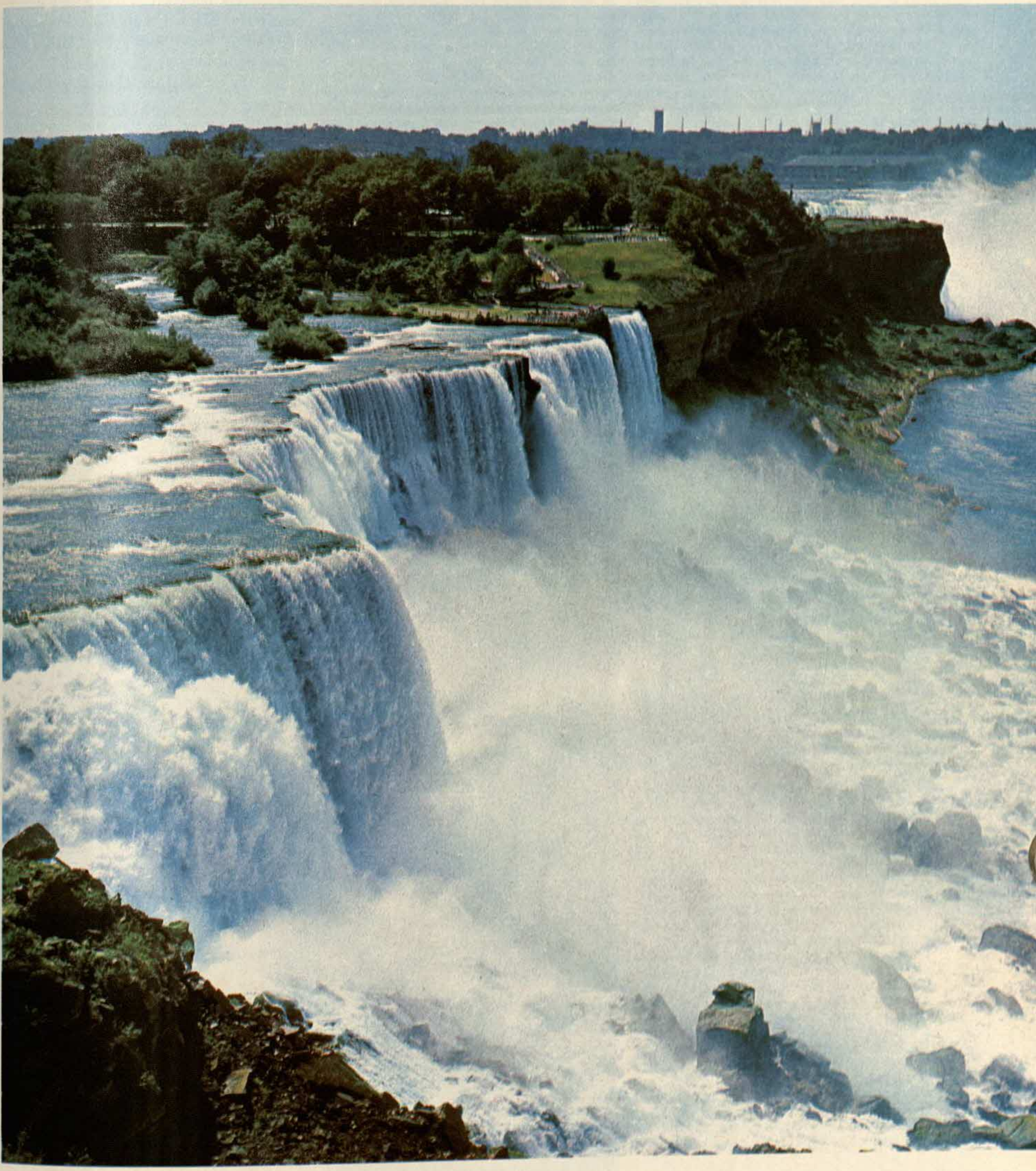


3b



RIVERBEDS

waterfalls and alluvial deposits



THE EROSIVE FORCE OF A WATERFALL—This mighty cataract (preceding page) is Niagara Falls, located between the United States and Canada, an obvious example of the erosion of horizontal rock strata. The water runs slowly over the horizontal rock layers, causing moderate erosion. A highly resistant stratum of limestone caps layers of softer rocks. As the water tumbles over the falls, its velocity and, consequently, its erosive potential increase enormously. The falling water erodes the soft shale at the base of the falls and gradually undercuts the limestone cap, weakening it. Eventually the overhanging part of the cap can no longer be supported, and great chunks of limestone break off, plummet into the gorge, and wreak ever more destruction on the soft rocks near the base of the cataract. Time and again, the cap or lip of the falls has been undercut with the same result. All in all, up to the present time, the falls have retreated a distance of seven miles, as the escarpment has repeatedly been cut back by erosion.

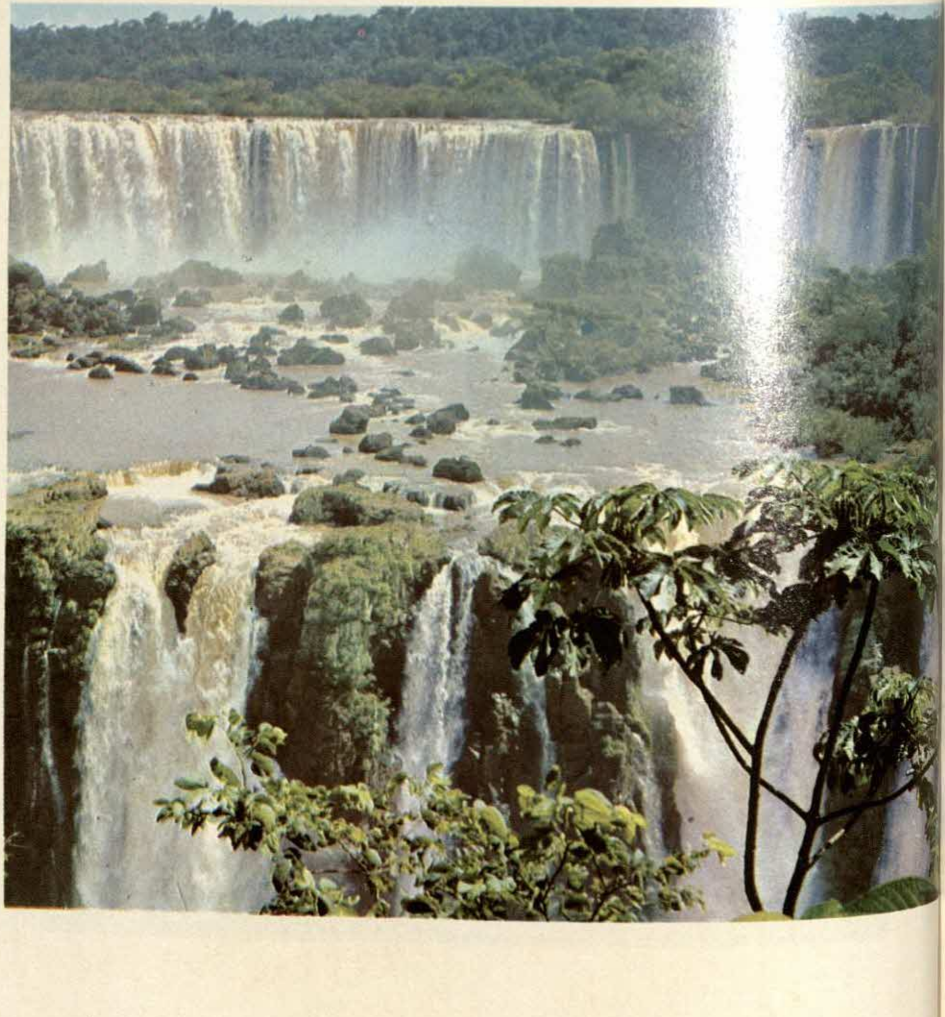
Great amounts of rocky debris accumulate in the gorge formed at the base of the falls; the water, having lost its velocity after its precipitous fall, is no longer able to carry away the rubble. Nevertheless, the constant pounding and churning of these rocks serves to break them into smaller fragments. Then, from time to time (as when the river is in flood), the volume of water carried by the river increases, and the velocity of the stream increases sufficiently to carry away some of the rubble.

Before considering changes in the forms of rivers and means of controlling their erosive and sedimentary actions, it is advisable to examine certain details of watercourses pertaining to waterfall formation and the permeability of riverbeds in the plains.

Waterfalls may be formed under varying conditions, but they are usually created where the stream bed consists of rocks of different degrees of hardness. If, for example, one section of a stream bed is made of hard, highly resistant rock, the two sections erode at different rates, and a discrepancy between the two sections develops. At first, the discrepancy is very slight, and this part of the stream is characterized by rapids. Later, as the differential erosion of the stream bed continues, the rapids will evolve into a waterfall.

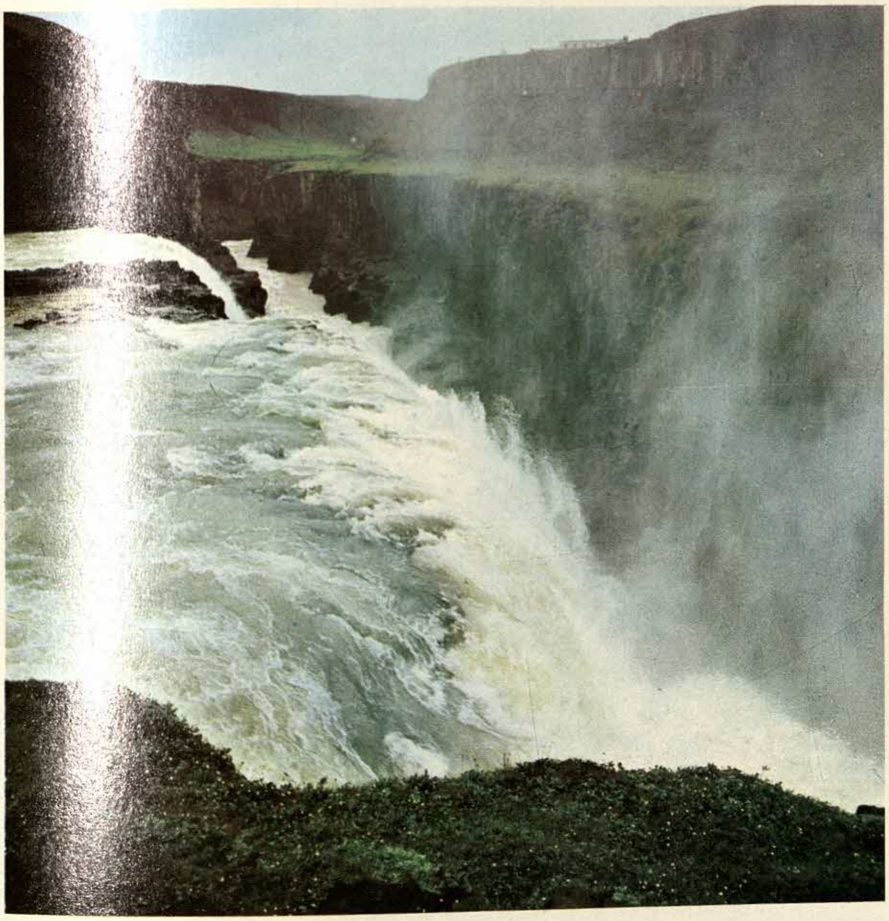
When a swift mountain stream enters a wide valley or plain, it begins to flow much more slowly than before, principally because of the abrupt change in the slope. As a result, huge quantities of detrital material carried by the stream are deposited around the mouth of the gorge. This detrital material, called alluvium, ordinarily is spread out in the shape of a fan; but if the alluvium consists of coarse material, it is spread out in the shape of a cone; hence, the entire deposit is known as an alluvial fan or an alluvial cone. Sometimes the alluvial deposits of several streams are connected to form an enormous piedmont alluvial plain. The Po Plain in Italy, for example, is covered with alluvium deposited by the Po River and its tributaries. The fertile, green plain of the Adige Valley, in the section between Bolzano and Rovereto, Italy, is filled with the alluvium of the Adige River itself. The Mississippi River flood plain is also alluvial.

The fact that these alluvial plains are covered with loose material (that is, sand and gravel not cemented together) accounts for certain special characteristics. This porous material absorbs great quantities of water. Indeed, more water moves underground in these extensive valleys than runs over the surface in the riverbeds. This is a factor of considerable technical importance in the building of levees, huge walls that run parallel to a river; levees must be built very solidly of waterproof materials to prevent the river in flood from eroding or overflowing them. It is necessary, however, to take into account the ground water, which is even more abundant when the rivers are in flood than at other times: after levees are built, during flood stage, water may gush out from beneath the ground beside the river but outside the levees.

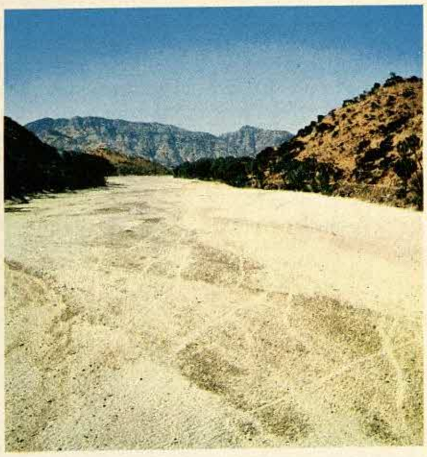


EROSION INTO TERRACES—The falls of the Iguaçu River in Brazil provide a picturesque example of erosion into terraces. Because the water runs over horizontal strata of rock, the falling of the water makes the face of the falls almost perfectly vertical. Between one fall and the next, erosion has created an almost horizontal flat area. The largest chunks of eroded material accumulate on this flat step, while the fine particles are carried away. In the falls that drop off from the center step, the yellow-brown color of the water is clearly visible; this color derives from the presence of minute particles of silt in suspension. The particles, evidence of the carrying power of the river, also serve as agents of erosion, for the rocks they touch are slowly but continuously abraded by them. The two faces of this waterfall are being cut back very quickly—that is, at a rate of several meters per century. In time, the constantly retreating falls may cut into softer rock or into rock that has strata with a different alignment, in which event the falls may be changed into rapids.

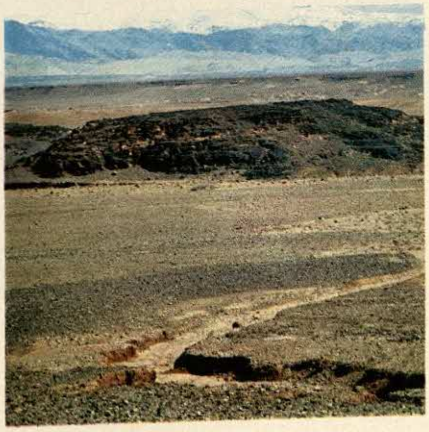
GUIDED EROSION—This river in Iceland has found a course in the bed of a former lava stream. The lava stream had cut away the valley on the right. The rocks of the valley on the right were much more easily eroded than those of the valley on the left, from which the greater part of the water comes. The left-hand valley is, therefore, shallower than the other, and the water flows from the left-hand valley to the right-hand valley over a waterfall. The fall of water further deepens the valley on the right, creating an ever-higher cascade.



A DRY WADI—In the semiarid regions of northern Africa and southwestern Asia, many stream beds are dry except during the brief rainy season. These stream beds are called wadis. The floods of the rainy season create violent streams, which carry large amounts of material eroded from the land; hence, the beds are filled with large quantities of alluvium, composed in general of material that is coarse and therefore loose and absorbent. When the water disappears at the end of the rainy period, its flow is still not entirely ended. In fact, for a long time after the water ceases to flow over the surface of the alluvium, the water continues to seep or flow through the alluvium-filled bed. Sometimes, water continues to move through this alluvial bed throughout the entire dry season. The photograph shows a very wide wadi near Agordat in Ethiopia.



TRANSPORTATION AND SEDIMENTATION IN AN ARID CLIMATE—An arid climate is characterized by an absence or paucity of precipitation; when precipitation occurs, it comes in the form of a cloudburst, and considerable quantities of water fall. The absence or near-absence of vegetation is another characteristic of an arid climate; rainwater, if it is not absorbed by the porous soil, flows rapidly, carrying with it whatever loose material is in its path. Here, in the desert at the foot of the high Atlas mountain chain of northwest Africa, may be found the debris from erosion that has been carried spasmodically to the valley by flash floods. During some heavy rainfalls, swift streams cut through earlier deposits.



THE EVOLUTION OF RIVERS

fluvial changes in time

In studying a river, it is convenient to consider it as divided into two parts. The first part is that which flows through mountainous terrain and is characterized by strong erosive action; the second, the part of the river flowing over the plain, is characterized sometimes by its eroding action and at other times by its sedimentary action.

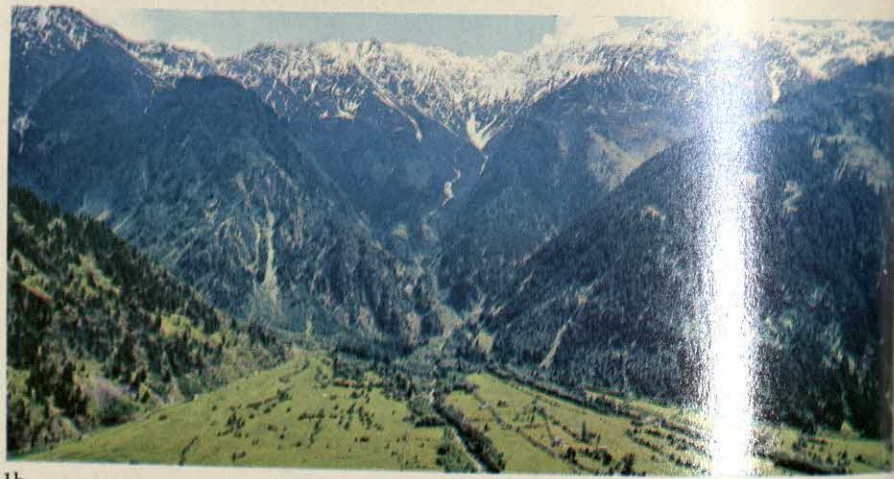
Erosion continuously deepens the stream bed and increases its stability. Any mountain stream, for example, cuts its way to the bottom of the valley, sinking between the steep sides. If the stream's flow increases, the water level

ALLUVIAL CONE—In an Alpine valley with a wide, flat floor (produced by glacial erosion) only slightly above sea level, the river is free to wind from one part of the valley to another. Occasionally, however, something happens to change the course of the river abruptly. This "something" is the deposition of materials that form a geological feature known as an alluvial cone. Alluvium is often high in organic matter that yields fertile soil.

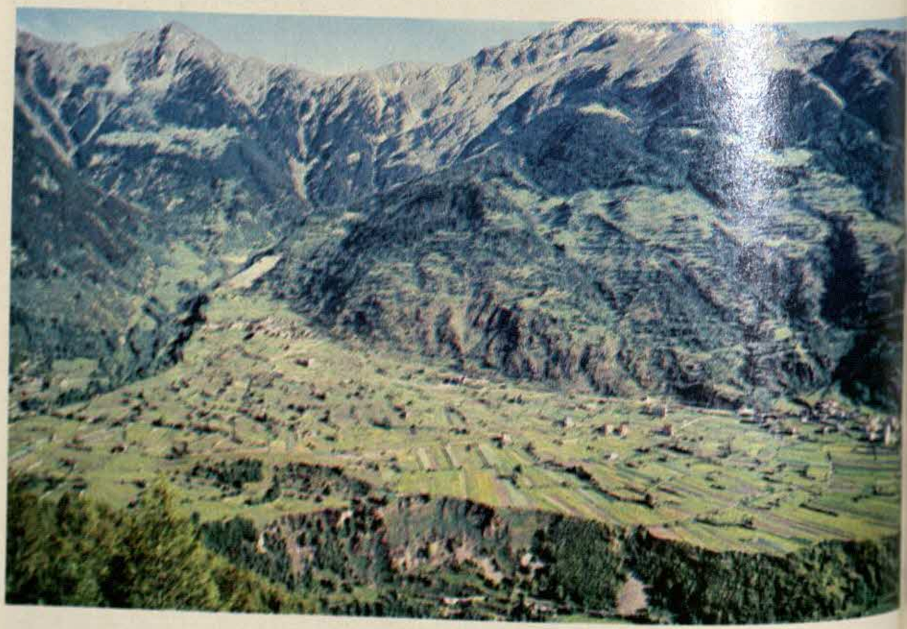
A valley with steep sides and little vegetative protection is subject, during torrential rains, to devastating floodwaters that descend into the valley at great velocity, carrying enormous amounts of loose (alluvial) material. Often this material is present in such quantity that the stream can best be described as a mudflow. In an Alpine valley, at any rate, this occurs solely because of the stirring up of vast amounts of rock-free alluvium (such as clay) that swells up in the water to form mud. When this alluvium flows into the valley, its speed decreases rapidly and the material is deposited to form a cone-shaped mass in contact with the sides of the valley. Frequently, no stream of water flows on the surface of the alluvial cone; because of the permeability of the deposited material, the water runs underground. At other times water flows along the surface of the cone, which in the meantime has been covered with vegetation (Illustration 1a). At the first ruinous flood, a vast amount of material flows down the mountainside to spread over the surface of the cone. (Such a flood may be caused by many factors, such as the accumulation of debris in unstable positions on the sides of the lateral valley, exceptionally heavy rainfall, or the loss of trees or other vegetative cover.) An alluvial cone is thus built up by a few floods, rather than by slow and progressive deposition of the loose materials.

The formation of an alluvial cone often forces the river running along the valley floor to change its course. Sometimes the sudden formation of an alluvial cone blocks the whole valley, and a lake is formed. Finally, the river may erode the cone, carrying away as much material as its torrential waters can hold, as in the photograph of an eroded alluvial cone in the Valtellina in Lombardy, northern Italy (Illustration 1b).

1a



1b



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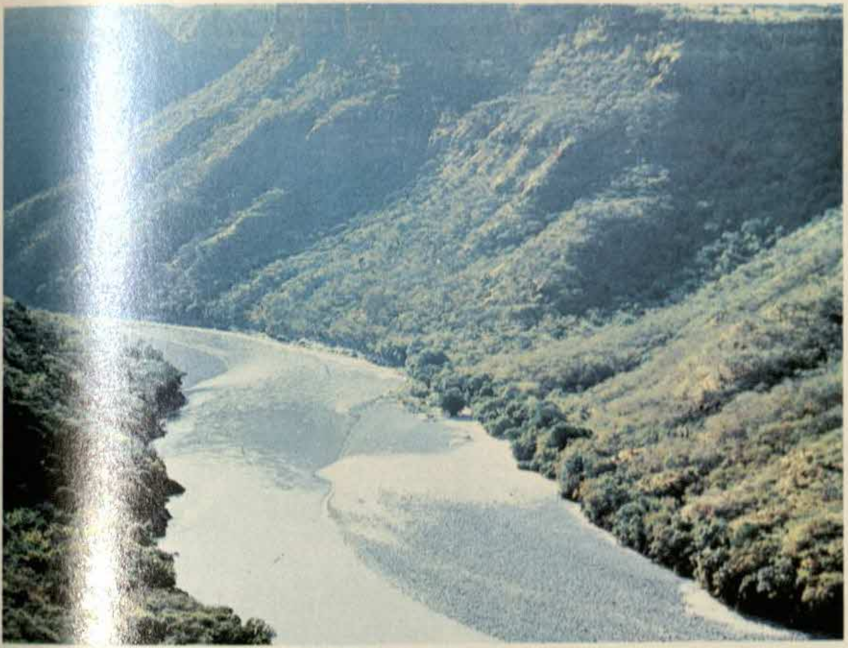


EROSION AND SEDIMENTATION IN RIVERBEDS—In that part of a river where the water moves slowly, it begins to wind and twist in characteristic meanders. To understand how these meanders are formed, it is necessary to study the river farther upstream where it flows through the mountains, guided in part by the sides of the valleys. This photograph shows a portion of the upper reaches of the Blue Nile near Lake Tana in Ethiopia. As the illustration suggests, the water, however slow its current, tends to be carried forward in a straight line by its own momentum; that is to say, the river tends to run along a straight bed and to cut the bed in a straight line. However, the position of the rocks and the sides of the valley force the river at a certain point to change direction abruptly. At the point where the watercourse changes direction, considerable erosion occurs. Here it is obvious that the river (as it comes in from the left side of the photograph) beats violently against the right bank and erodes it (to the point where it now appears as a sheer face with vegetation jutting out of the water). The current, its course having been altered, next strikes the left-hand bank, eroding it forcefully, too. On this side of the river the rocks have been bared by the erosion. Conversely, on the inside of the bend, the water flows slowly—chiefly because most of the water is thrown to the outside of the bend. On the inside of the bend, the slow-moving water deposits much of its solid material, thus widening the bend in the shape of an S.

3

A USELESS BRIDGE—The ancient Romans built this bridge over the Adda River in Valtellina almost 2,000 years ago. The river changed its course and today flows several hundred meters farther north; the bridge, therefore, is totally useless, even though its robust construction withstood the floods that filled the bed of the Adda. Today it serves as a reminder of the speed with which the face of the land can be altered by geological changes.

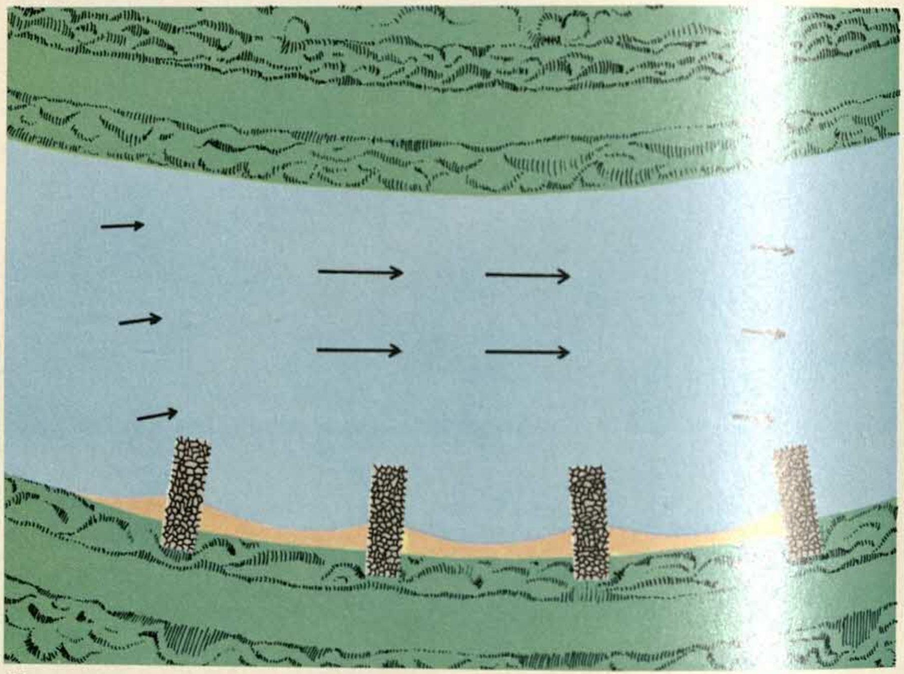
increases a little as well, but the stream never overflows its banks because it is confined within steep, high walls. The end result, of course, is a further deepening of the channel. The eroded material is carried far downstream.

When the river reaches the plain, it no longer behaves as a mountain stream. During flood stage, it carries vast quantities of material toward the sea; however, when the water level drops, much of the material carried in suspension and stirred up by the current is deposited on the riverbed. This material may be removed from the bed by the next flood—provided that the bed itself is not changed in the meantime. This stretch of the river, therefore, is characterized by sedimentation, which affects it considerably. Where the sediments are deposited, the riverbed is built up; in time the bed can no longer hold the waters of the stream, which then seeks a new route.

Rivers have changed their courses many times through the centuries. However, it obviously is not always desirable that this should happen, especially when the area bordering a river is densely populated or under cultivation. Therefore, it is necessary for scientists, engineers, and civic leaders to understand the causes of this phenomenon and to recognize its advance symptoms. Naturally, once these facts are known, countermeasures may be taken.

HOW THE BANKS OF A STREAM BED ARE PROTECTED—When a bank of a river has been lined with a levee, there is grave danger that the increased erosive action of the water at a bend—particularly when the river is at flood stage—may batter the levee to pieces. However, the river itself may be forced to deposit sediment against the levee, thereby protecting it; this is accomplished by constructing walls extending out from the levee at right angles to the current. The water erodes the ends of the walls; but before it has destroyed them, it deposits a great thickness of sediments between one wall and the next. Between the walls the current slows enough to drop its solid materials. After some time, even though the walls may have been destroyed, the portion of the levee attacked by the current will be protected by the sedimentary deposits. On the opposite bank, the erosive action of the river is increased; instead of depositing its solid materials there as formerly, it now carries away material because it moves with greater speed than before.

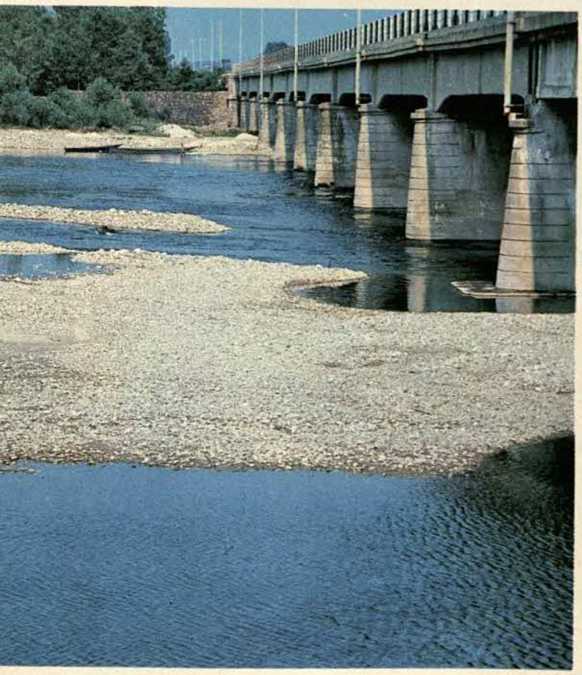
4



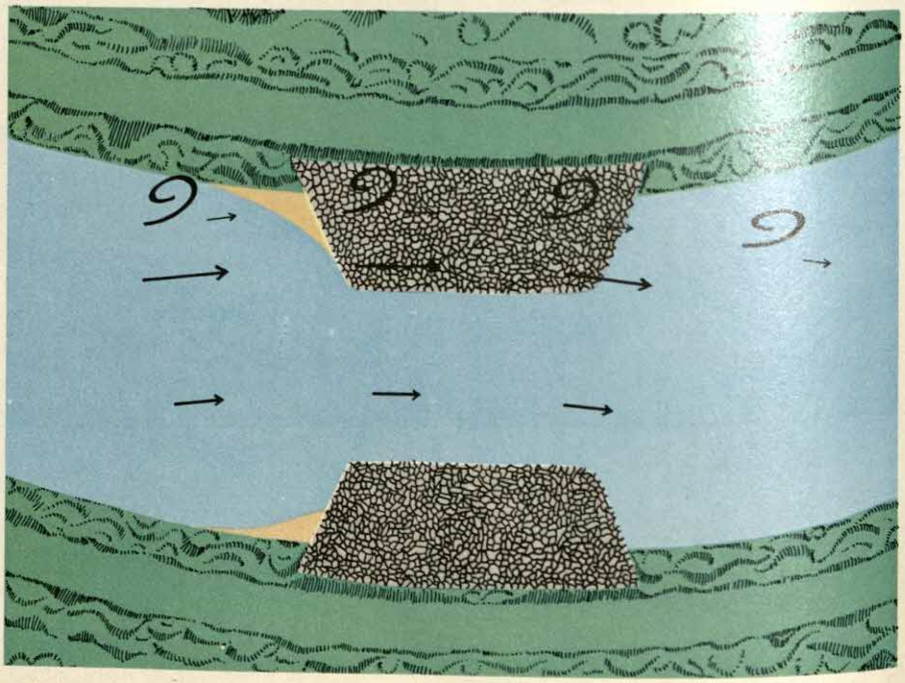
FREEING RIVERBED BLOCKED BY SEDIMENT—When a river is provided with levees, it can be left to choose any course it wants within the confines of the levees so long as it does not come too close to either levee and erode it. In time, however, sediments will fill in the bed, creating a hanging river—that is, a river that is higher than the surrounding plain. If the river should break through one of the levees during a high-water period, it would cause a disastrous flood, for it would be difficult to force the stream back between the banks.

Nothing can be done to prevent the filling in of the bed. Sometimes, however, it is useful to cause part of the sediment accumulated near a bridge to be washed away so that the current will not attack the piers of a bridge (Illustration 5a). To free a riverbed of sediment is a sizable operation, and often it is not economical to engage in dredging operations. Fortunately it is possible to use the river itself to obtain the desired results. If a second levee is built on the larger levee (Illustration 5b), the water is channeled into a narrower passage and the increased speed of the river will carry away the sediment and deepen the river channel.

5a



5b

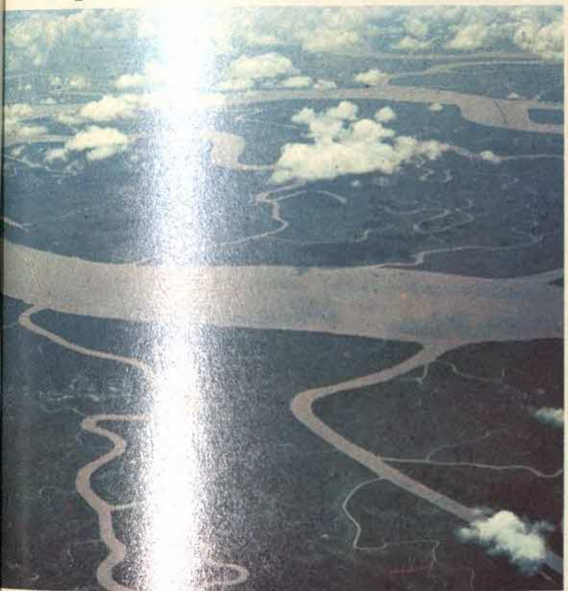


MEANDERS | the ever-changing course of a river

A river, like a living organism, is born, develops, and grows old; during its life it changes continuously—slowly as a rule but quickly when it is in flood. The evolution of a river is visible in the mountains where, because of the steep slope of the riverbed, the swiftly flowing water erodes the bed, carrying silt, sand, gravel, and larger rocks to the valley.

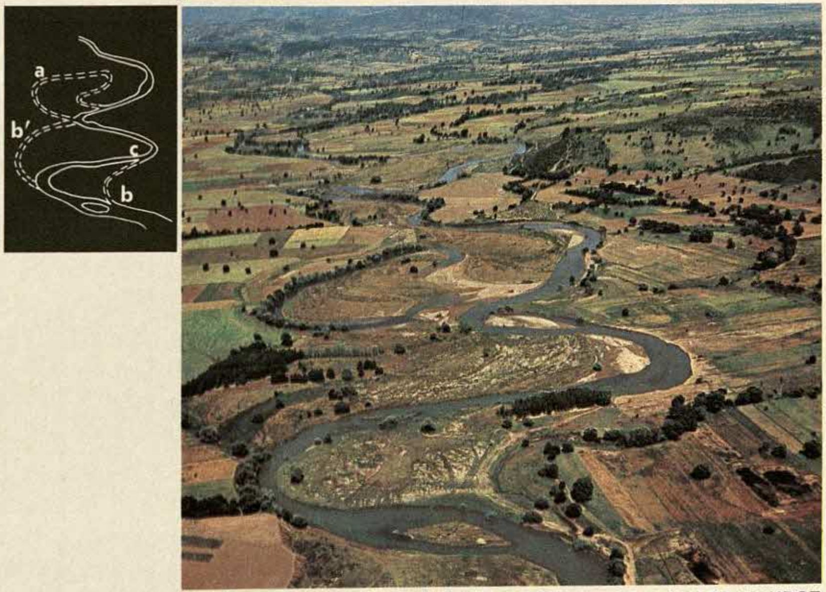
On the plain, where the inclination of the riverbed is slight, a large part of this eroded material is deposited, filling the riverbed little by little. However, even here, where the water flows more slowly than in the mountains, the river undergoes constant change, twisting and turning (meandering) through the relatively flat plain. The word *meander* derives from the name of a river in Asia Minor, the Maiandros, which had a serpentine course. A river with this kind of course is in continuous evolution. The meanders shift, widen, and narrow unceasingly; sometimes they disappear, and for a while the river courses in a relatively straight line. Men must interfere sometimes and straighten it themselves.

1



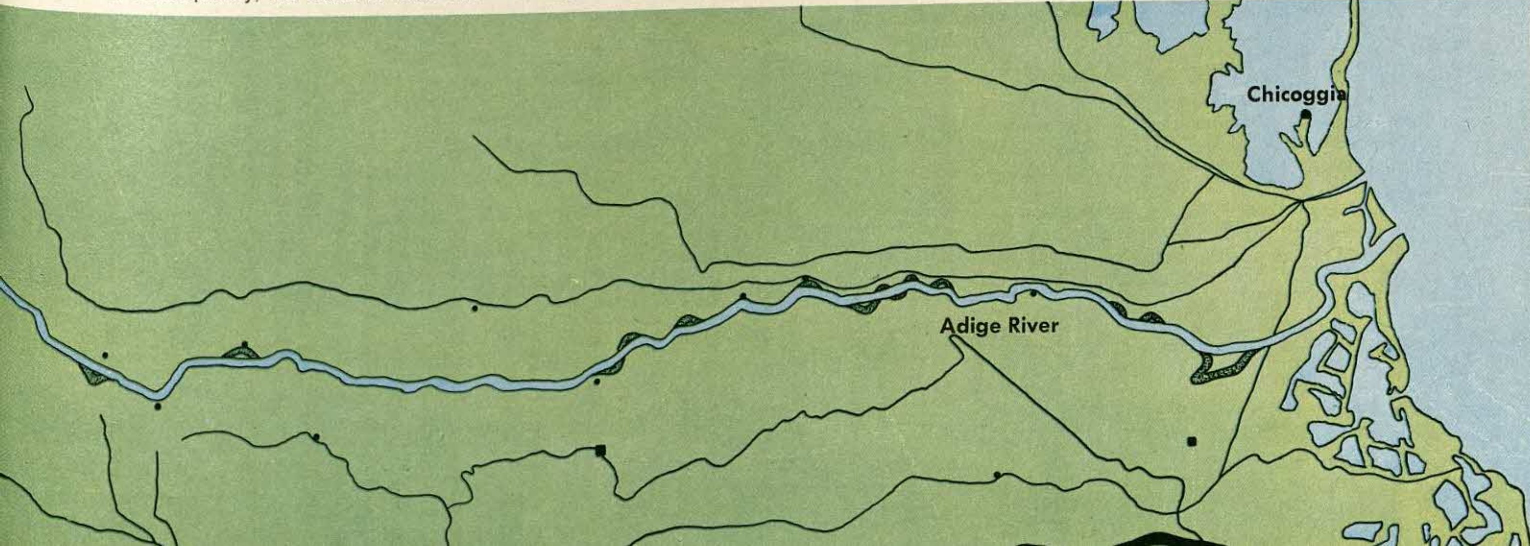
THE DELTA OF THE GANGES—A river that meets the sea after having run over flat, slightly inclined terrain usually empties into an area that has been filled with its own sediment. To reach the sea, therefore, such a stream must open a channel through the sediment itself; or, after a certain amount of sediment has been deposited, it must cut a new course to the sea, one that avoids the deposited material. In time the sedimentary accumulation extends into the sea, forming a delta. Because the delta is flat, the river flowing over it is serpentine; in addition, the river often divides into a thousand smaller streams of different sizes. The photograph shows the delta of the Ganges where it flows into the Indian Ocean in East Pakistan. The continual changes in the courses of the many small streams serve to maintain the uniform distribution of the sediments on the surface of the delta; consequently, the delta remains flat.

2



THE STRAIGHTENING OF A RIVER COURSE—The river shown above flows in Turkey, and follows a winding course. The photograph shows how some meanders have been abandoned. The diagram reproduces the stretch of river shown in the photograph. The meander identified as **a** in the diagram has been abandoned recently and has the typical crescent shape of an oxbow lake. As this meander continued to grow, it came into contact with the next meander, and the course of the river was shortened. For a short while afterward the abandoned meander contained water; then it gradually became filled in and covered with vegetation. Lines of trees, indicated as **b** and **b′**, show the course of the stream before these beds were cut off and abandoned a long time ago; now the vegetation is the only outward sign of the event. The progress of sedimentation in the inner part of a bend is identified as **c.**

3



STRAIGHTENING MEANDERS ARTIFICIALLY—Sometimes men have found it necessary to intervene in the natural evolution of rivers. A river left free to meander widely over a plain finally slows in its course and deposits vast quantities of sediments on the plain. If the river is contained by levees, it may easily fill the bed between the levees with sediments and become a "hanging" river—a river that runs above the level of the surrounding plain. Therefore, it is often convenient to cut through the land separating two meanders, thus straightening the river's course. This straightening produces several beneficial effects: in the first place it keeps the river from running over too wide an area and leaving too little ground for cultivation; in the second place, the current is made to run faster and the bed of the river is partially cleared of its sedimentary deposits, eliminating the need for enlarged levees. The Adige in Italy has been straightened.

THE MECHANICS OF MEANDERING—A river that runs straight is unstable, because the smallest disturbance of its course is enough to make it bend. This series of illustrations shows how meanders are created and changed in time.

Illustration 4a represents a straight watercourse. It is not a canal, but an imaginary river flowing over a plain, on a bed of sand and gravel. (In the illustrations the river flows from right to left). The current easily erodes such a bed and carries away the material. The river continues to run in a straight line only if the bed is perfectly straight and composed of perfectly homogeneous material.

The deposition or accumulation of even a small amount of material at any point on the bed is sufficient to cause the current to be deflected by this obstacle (Illustration 4b). In this case the water is diverted to the right (the right of a river is the right as one looks downstream toward the mouth). The current which runs near the bank is directed toward the right, instead of running parallel, and flows against the bank, eroding it, at the point shown. On this side the bank is thus gradually eaten away.

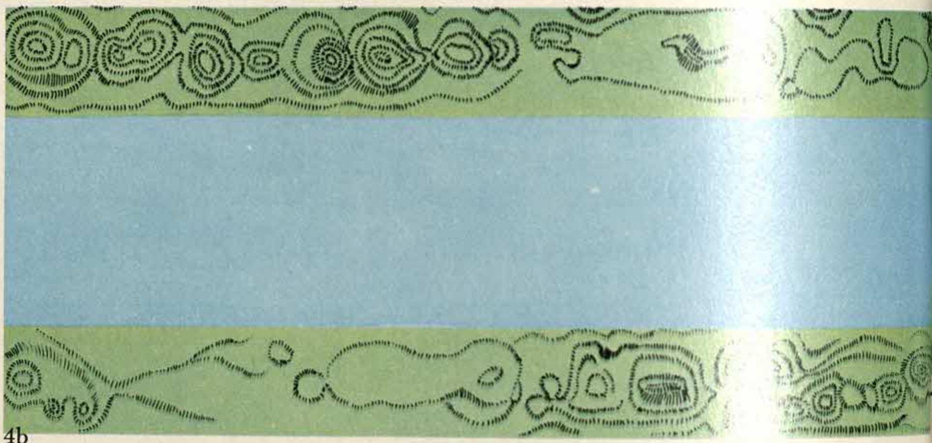
Because of the erosion of the bank the water pushes ever further into the curved bed, away from its former path. The water, having flowed against the new detour it has created, must return to the straight path of the old bed; however, it re-enters the old bed at an angle to the axis of the bed and flows against the left bank further downstream, eroding it (Illustration 4c). This creates a new detour through which the water runs, always cutting away along the outside of the bend.

By now a meander has been created, and it slowly continues to enlarge itself (Illustration 4d). The meander consists of two curves rounded along their outside edges; because the fluid current is always stronger near the outside of the curve, the meander continues to be eroded and enlarged. At the same time, the material eroded from the outer edge of a curve is deposited along the inside of the successive bend or bends. Thus, in practice, both a continual widening of the bend and a continual shifting of the current toward the outside occur.

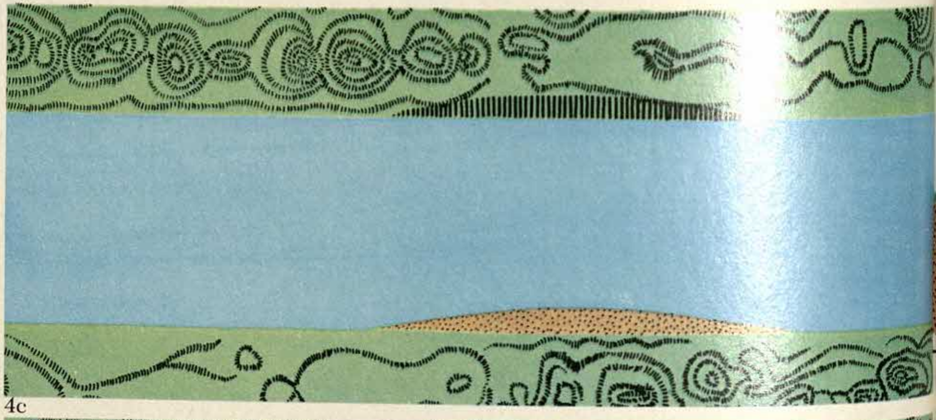
Illustration 4e represents an asymmetric section of a stream bed on the outer part of a bend; the greatest depth is near the outer edge, while toward the inner bank the water gradually becomes shallower until it disappears. Correlatively, the speed of the current varies from a maximum where the water is deepest, to a minimum where it is shallowest. This is another reason for the difference in the degree of erosion along the two sides of the bend.

With the accentuation and progressive enlargement of the bends, the course of the river is considerably elongated (Illustration 4f). To flow from point **a** to point **b** the water no longer covers, for instance, 500 m, but three times that distance. Inasmuch as the difference in elevation between the two points remains the same, the average inclination of the stream bed is reduced; the average velocity and erosive potential of the current are reduced proportionately. As a result, sediment is precipitated more quickly than before, and the bend becomes unstable. In fact, the curve or bend of a meander may enlarge itself again and again until it comes into contact with the next bend. Then, suddenly, the water changes

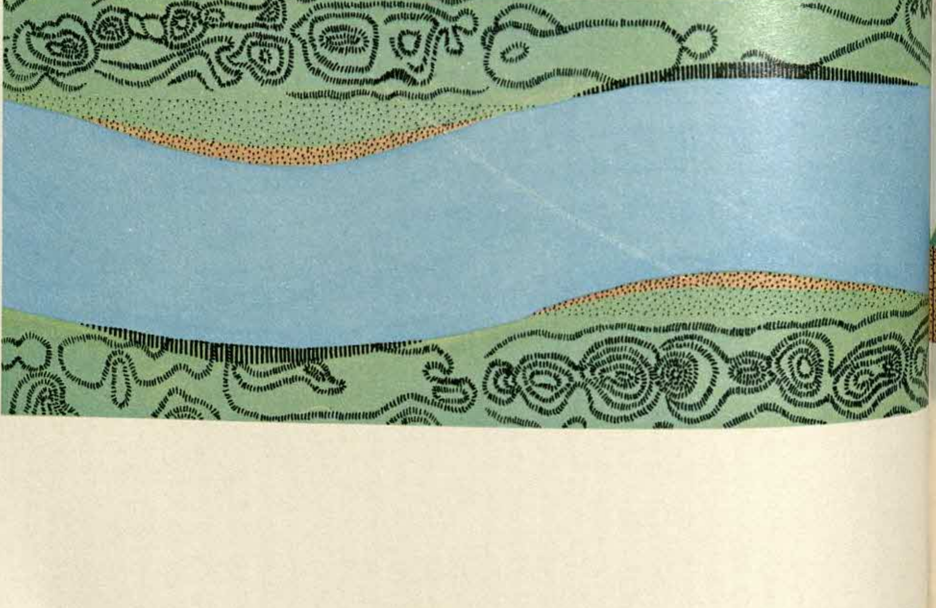
4a



4b



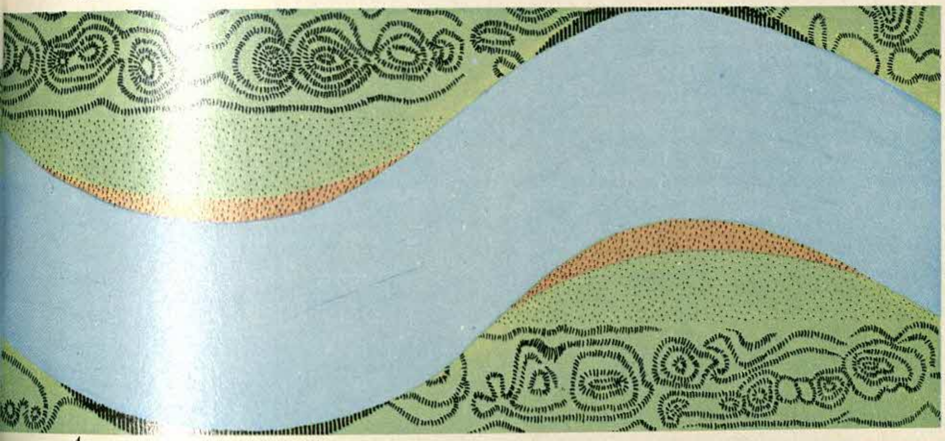
4c



its course, flowing directly from one bend to the next without following the course of the reverse bend. Often during a sudden rise in the water level, the stream will cut through the land separating two successive bends, eliminating the reverse loop in this way.

The meander has been abandoned (Illustration 4g), and the bed remains for a while filled with stagnant water. Such an abandoned meander is often called an oxbow lake. In time it becomes covered with vegetation and disappears.

4d



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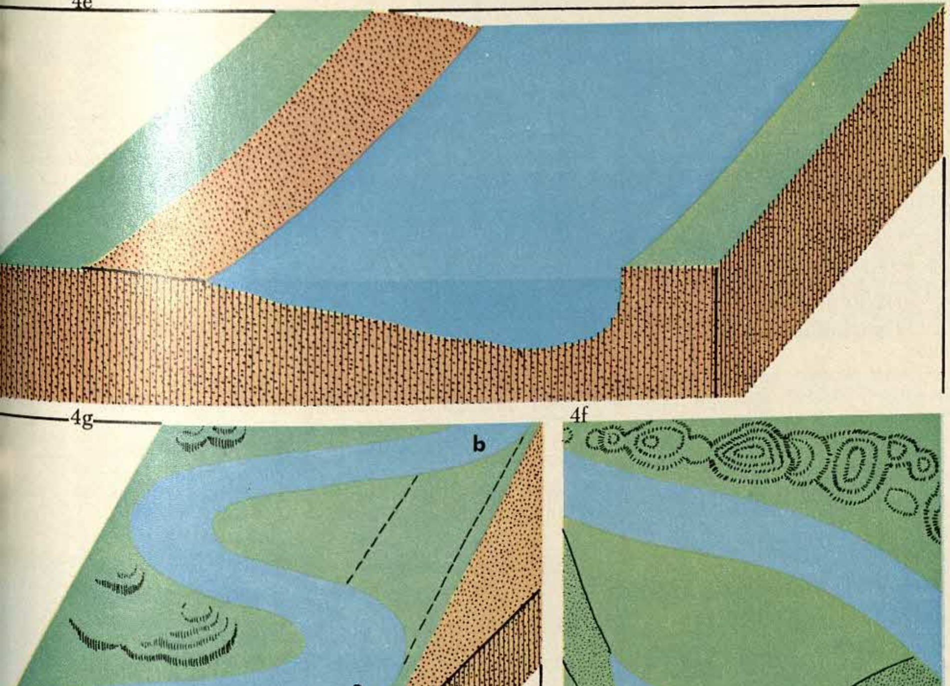

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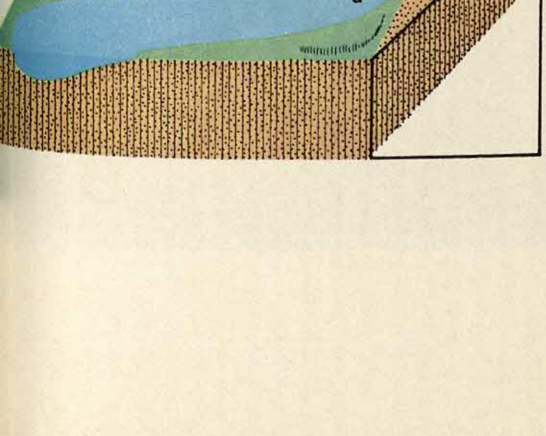

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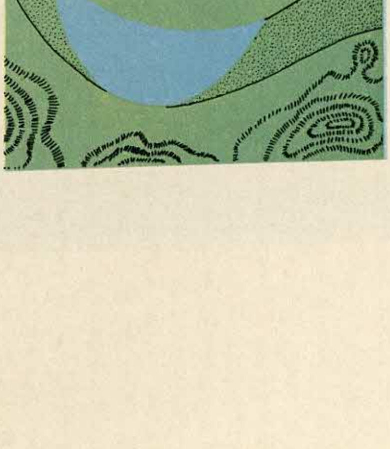


5

THE LAST MEANDER—The River Jordan changes direction for the last time just before it empties into the Dead Sea; the mass of sediment on the right forces the stream to flow to the left. This mass of sediment is thus eroded, and as the depth and speed of the stream are greatest where the water eats away at the sediment, the material which falls from the bank is immediately carried away by the force of the water.

6

MEANDERS IN A PLAIN WITH IRREGULAR TOPOGRAPHY—When a river flows over a flat, wide valley of only slight inclination, given enough time, it meanders over the whole expanse of the valley. Almost all of the sediment covering the valley floor is carried away, albeit very gradually. First, the material is carried from the outside of one bend to the inside of the next bend; then, when the river changes its course and the place where the sediment was deposited becomes the outside of a new bend, the material is carried a little farther down the stream bed. On the other hand, when a river flows over a plain with an irregular topography, it does not flow in nearly identical meanders; instead, it runs from right to left, following the line of greatest inclination. The river shown in this photograph meanders over a plain in the southern part of Iceland.

LAKES | evolution and characteristics

Lakes are bodies of still water, usually basins in which rainwater is contained for a while before it evaporates or flows on toward the sea. Lakes are subject to rapid evolution, and hence have brief lives in terms of geologic time. Unless a lake is very deep, silt and decaying plant matter deposited on its floor may, in a relatively short time, turn it into a marshy area and then dry land.

Although the geologic history of a lakeshore is the brief history of only one spot on the Earth's surface, such history may be of great interest. Lakes are formed in many different ways, and knowledge of a lake's history may aid in reconstructing the history of the entire surrounding region. The study of a lakeshore may also aid in reconstructing the history of certain civilizations. Ancient peoples, forced to migrate for one reason or another, often found lakeshores favorable places to establish their villages. Additionally, by studying the soil of extinct lakes, scientists gain knowledge of plants and animals that lived long ago.

There are also practical reasons for studying lakes and the life within them. Lakes are valuable as a source of edible fish. Even more important, lakes collect and store water that can be used for irrigation and for the production of electric power.

Lakes have almost universal distribution; but they are most abundant in high latitudes and in mountain regions, particularly those that were glaciated recently. Lakes are common along rivers that have low gradients and wide flats, showing a clear connection with the changing channel of the river. Lowlands near the sea, especially in wet climates, have countless lakes. Florida is a good example. The primary source of lake water is atmospheric precipitation. It may reach the lakes by means of rain, melting ice or snow, springs, rivers, and immediate runoff from the land surfaces. Lakes may be fresh or salt water. Some are saltier than the sea. Lakes vary widely in size also. The Great Lakes of the United States and Canada constitute the world's greatest array of large lakes. Their combined area is 246,400 km^2 (about 95,000 mi^2).

LAKE BASINS—Lakes are classified according to the origin of their basins. The lakes shown in these photographs occupy basins that were formed in different ways.

The very largest, deepest lakes generally occupy basins that were created by a large syncline or tectonic depression. Such lakes are long-lived; nothing except another major movement of the Earth's crust is likely to destroy them. Lake Aral (in Soviet Central Asia) and the Caspian Sea are lakes of this kind; in fact, they were once linked together during the Tertiary period several million years ago, and during the upper Miocene epoch they were also linked to the Black Sea and the Mediterranean. Although these lakes are now isolated from each other, they will remain for a long time, as they are of considerable depth and size. In North America, Lake Superior and Lake Michigan were partly formed by downwarping of the Earth's crust. Illustration 1a shows Lake Kivu in Rwanda, one of a number of African lakes of tectonic origin.

Some lakes occupy basins that are the craters of extinct or dormant volcanoes. Since lava is impermeable, rainfall collects in the crater and remains there without seeping down into the underlying soil or rock formations. Illustration 1b shows Lake Vico, one of the many lakes of central Italy that are of volcanic origin. Crater Lake in Oregon is a well-known example of this kind of lake.

Where highly soluble limestone lies under the soil, the seepage of surface water through fissures in the rock may dissolve the limestone, thereby creating caves containing underground lakes. The kind of area in which this occurs is termed karst topography. Illustration 1c shows a portion of the underground lake in the grotto of Castellana, in Italy. The sinkhole lakes common in north central Florida and other karst regions of the United States form where the roof of a cavern collapses and the resulting depression fills with water.

Glacial erosion has created a great many lakes. In Canada and the northern United States, Finland, and Sweden, thousands of lakes fill shallow depressions scooped out by the continental glaciers. In the Alps and in other rugged mountain areas, lakes occupy deeper basins carved out by alpine glaciers. Lake Como, shown in Illustration 1d, is about 400 m (about 1,300 ft) deep at one point; its surface is about 200 m (about 650 ft) above sea level and its floor is about 200 m below sea level. Like most other mountain lakes, Lake Como is of glacial origin, as are most of the world's present lakes.

In alluvial plains occur lakes of a type called phreatic (Illustration 1e); they contain underground water that has been brought to the surface by some underground irregularity.

A special type of mountain lake is the cirque lake or tarn, which fills a round, steep-sided basin high on a mountainside. As an alpine glacier moves downslope, water seeps into cracks in the exposed rock, freezes, and expands. The rock breaks apart and is carried away by the glacier. Lake Mucrone (near Biella, Italy), shown in Illustration 1f, occupies a basin that was formed in this way.

A lake may form where a stream is dammed by a landslide or by the slow deposition of sediment. Such naturally formed dams are often unstable, and the pressure of water building up behind them causes them to break. When this happens, the water in the lake floods the valley below. Such floods are common in the Himalayas, where the breaking up of a glacier may create a dam of ice mixed with morainic material. When the water reaches a certain level, it will melt the ice and undermine the dam. When a landslide blocks off an inhabited valley, explosives or other means may be used to destroy the dam before too large a lake forms behind it. Lake Alleghe, shown in Illustration 1g, was formed when a landslide created a permanent and impermeable dam across an Italian mountain valley. When the water level reached the top of the dam, the stream flowed on along one side of the valley.

Another kind of naturally formed dam may create lakes at the edge of the sea. Where the sea is shallow and the bottom sandy, wave action builds up a sandbar a certain distance from the shore. If the sandbar becomes attached to the shore at each end, the body of water behind it becomes a lake. The Italian lakes of Orbetello, shown in Illustration 1h, were created in this way. The same process created the lagoon of Venice, which is not yet a lake completely isolated from the sea.

1a

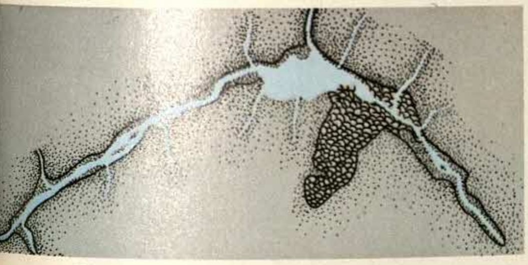
1b

1c

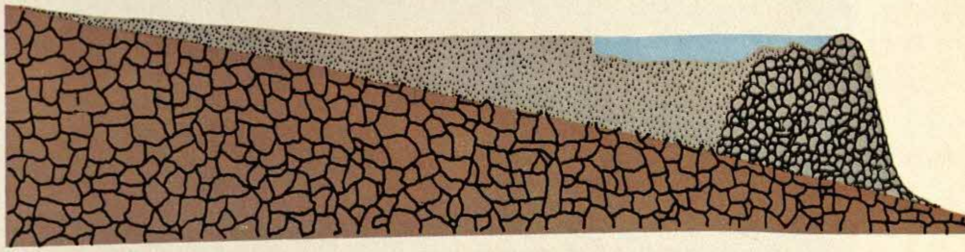
1f

1d

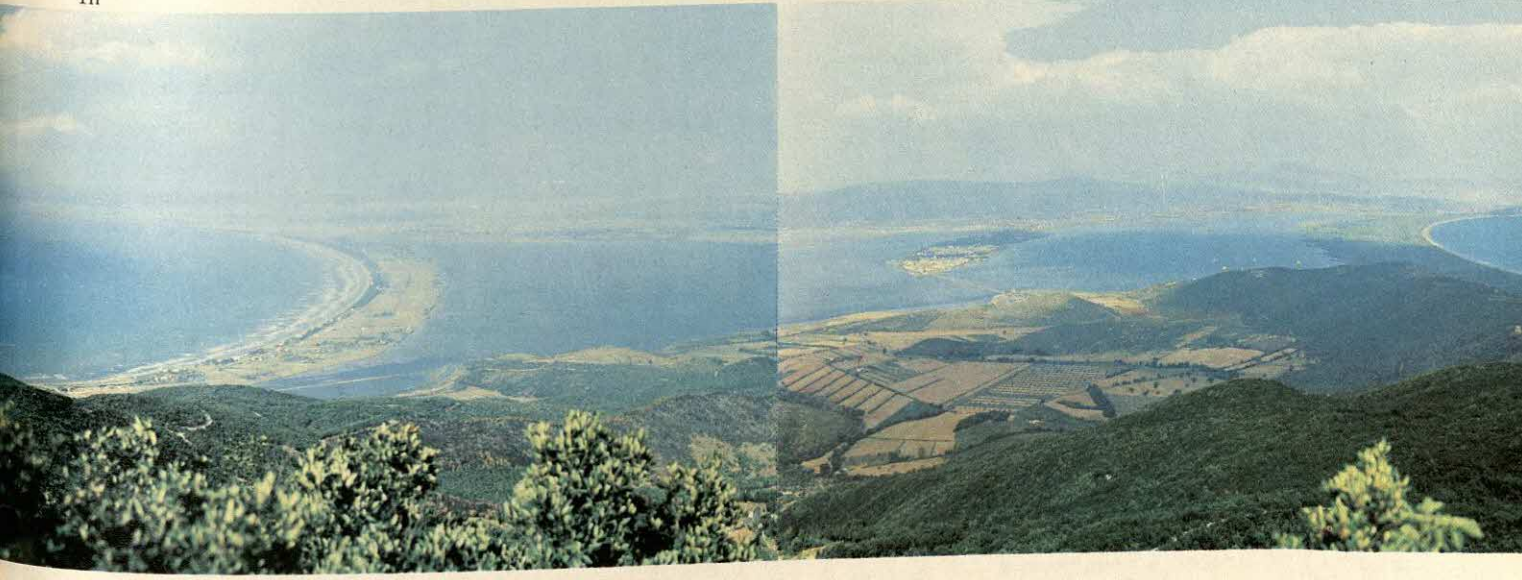
1e



1g

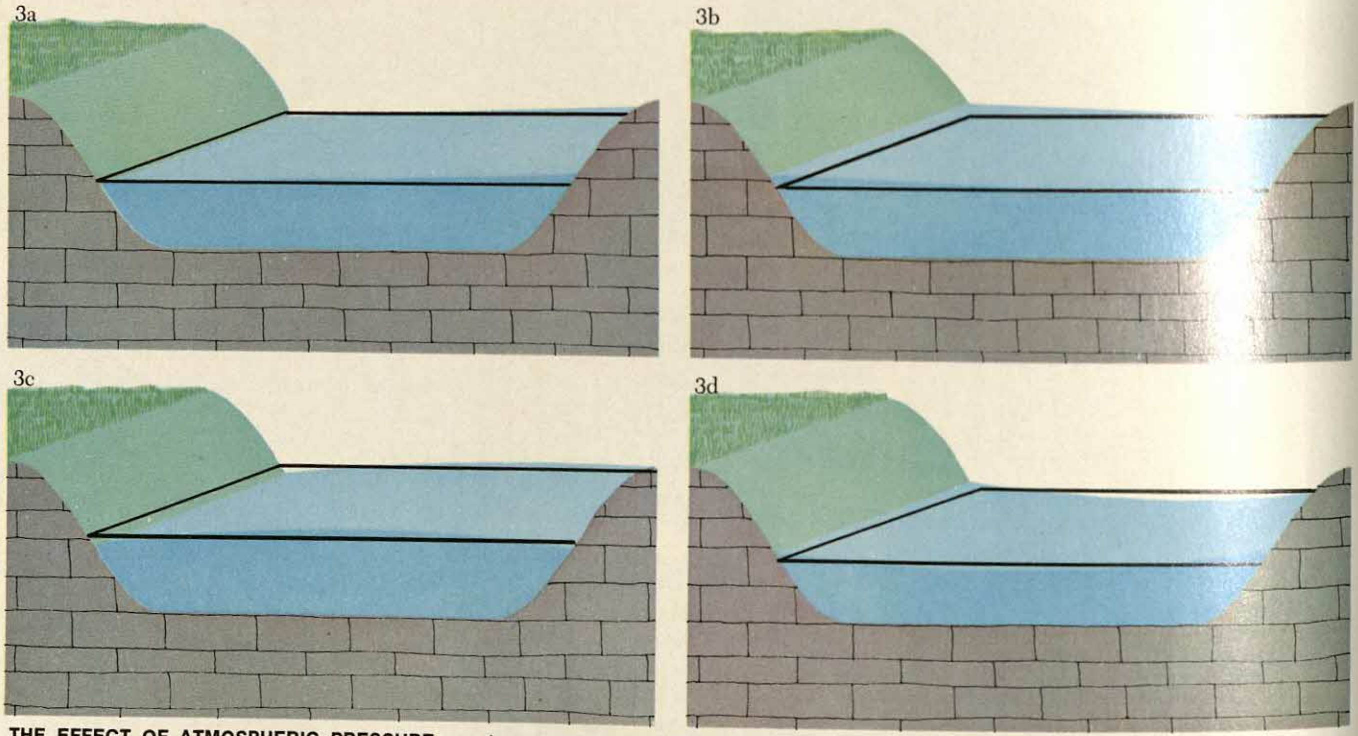


1h



2

THE INFLUENCE OF A LAKE ON A RIVER SYSTEM—This large man-made lake was created by damming the North Platte River in Wyoming. The important function of such a lake is regulating the flow of water downstream. To prevent seasonal floods, excess water is impounded behind the dam; the water is released when the river is low. Because the lake is calm, sediment carried in by the feeder river precipitates, and the water that leaves the lake is clear. If the lake is large, solar heat stored by the water may have a moderating effect on the local climate.



THE EFFECT OF ATMOSPHERIC PRESSURE ON THE LEVEL OF A LAKE—Lake water is never completely still; it is subject to several kinds of movement. One type of movement, which is negligible, is the flow of water from inlet to outlet; the amount of water involved is so small, compared to the amount of water in the lake, that this movement is seldom observed. Currents are also caused by temperature differences in the water and by winds; these currents are similar to the currents of the oceans. The winds also raise waves, but unless the lake is very extensive, the wave motion has little effect on the evolution of the lake itself.

An unusual kind of movement in lake waters is the rising and falling of the water level in response to changes in atmospheric pressure. When the banks of a lake are mountainsides, the heat of the sun may cause a strong upward current of the air at one side of the lake and a downward current of the air at the opposite banks, which in turn causes a difference in the level of the lake surface. For every centimeter of difference in atmospheric pressure, the level of the lake rises or falls 13 cm (about 5 in.). (The ratio of 1 to 13 is that of the density of water to the density of mercury, with which atmospheric pressure is measured.) Such a difference in atmospheric pressure may impart an oscillating motion to the lake water, as shown in Illustrations 3a and 3b. The oscillation may also take the form shown in Illustrations 3c and 3d, or it may occur as a combination of these two forms, or in other forms still more complex. This oscillatory motion, which is sometimes called a seiche, may continue long after the difference in atmospheric pressure that caused it ceases to exist. The extent of the oscillation and its duration depend on the size and depth of the lake. Large lakes oscillate to a considerable extent and can have a long period of almost an hour, while small lakes oscillate only slightly with a short period of minutes.

THE LIFE AND DEATH OF LAKES

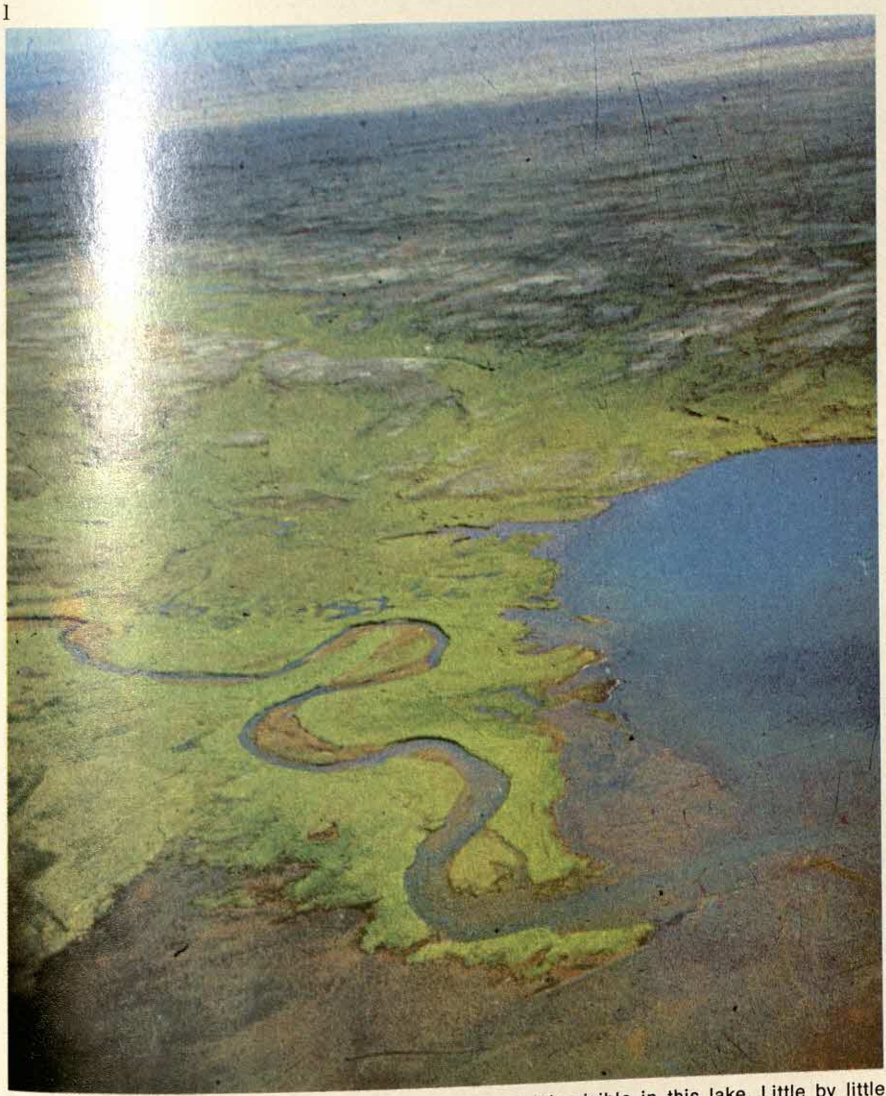
A lake is not so much a geological structure as a passing phenomenon in the history of the Earth's surface. Lakes millions or even tens of millions of years old do exist—the Caspian Sea and the Aral Sea, for example—but these are actually more inland seas than lakes. Lakes generally have brief lives, geologically speaking, because the very factors that give them birth also cause their death.

THE FORMATION OF LAKES

Lakes are caused by the formation of a depression or groove in the crust of the Earth, or of a barrier that dams up a valley, creating a basin in which water collects. This water comes from four main sources:

1. The affluence (flowing in) of watercourses. Often a lake has one main affluent (tributary stream) and a number of lesser streams to feed it. Italy's Lake Como, for example, is supplied chiefly by the Adda River, which flows into it at Colico; but it is also fed by countless small streams that start in the mountains surrounding Lake Como.
2. Affluents below water level. The invisible flow of water into a lake is often greater than the visible inflow. Underground streams flow between impermeable rock layers, and may flow into a lake in sufficient volume to offset loss of water from various causes. Almost all lakes at desert oases are supplied in this way.
3. Rain that falls directly into the lake.
4. The condensation of atmospheric water over the cold surface of the lake. On contact with the surface, the damp air gives up part of its water.

1



A RIVER FEEDING AN ICELAND LAKE—Because of the transparency of the water, the various sediments brought down by the river are plainly visible in this lake. Little by little, it will be filled by the sediments.

THE DEATH OF LAKES

All lakes eventually disappear because they lose water in these ways:

1. In most cases a river on the surface carries away the water supplied by the affluents.
2. Water flows out of the lake underground. This generally occurs when lakes are situated on porous soil that is completely permeable (alluvial soil, for example), or on nonporous material that nevertheless contains gaps and cracks (calcareous rocks, for example). In either case, water loss is considerable.
3. Water escapes through evaporation. In very dry climates this can be the main cause of water loss. The larger the surface of the lake, and the shallower it is, the greater the evaporation. When a lake is shallow, the entire body of water becomes warm, increasing evaporation. Other factors causing evaporation are frequency of sunlight and low humidity in the atmosphere.

Many lakes dot the surface of the Earth today only because many factors continually combine to bring new lakes into existence. The survival of a lake is determined by the rate at which it drains and refills. A lake may dry up for many reasons—among them evaporation, which can eliminate a lake when the rate of evaporation is greater than the affluence of water. In an area that has been reforested, or has become dry for climatic

2

LAKE TITICACA (PERU)—Large lakes such as Titicaca in the Peruvian Andes have relatively long life-spans running into millions of years. Lakes formed by glacial erosion have shorter life-spans that can be reckoned in tens of thousands or perhaps hundreds of thousands of years. Lakes created by dams caused by landslides sometimes last only a few years—at most, for a few centuries.

reasons, the affluent may dwindle to such an extent that the lake simply evaporates. Such has been the fate of lakes in arid regions, and of the salt lakes of Africa, North America, and Australia.

Lakes formed by underground water inundating a porous subsoil may disappear simply because the water table drops. Such lakes are found on alluvial soils; a sand and gravel pit, which is a source of typical alluvial materials, will fill with water after digging has reached a certain depth because the subsoil has become completely inundated with water.

Lakes formed by dams sometimes erode the dam that encloses them, allowing the water to pour through the breach until the lake is empty. Lakes with rocky basins sometimes dry up as a result of water erosion. Lakes located on the kind of soil of which the Carso—a limestone area along the Dalmatian coast of Yugoslavia—is typical lose part of their water through underground tunnels. As the water rushes through the tunnels, it gradually enlarges them until the drain from the lake has become massive.

Lakes of tectonic origin—those situated in synclines (folds) or trenches in the crust of the Earth—generally have a longer life-span than others of different origin. Some tectonic lakes, with vast basins that require millions of years to fill, often change size according to the variations in tectonic conditions. The Caspian Sea and the Aral Sea, for example, were once joined to form one lake far larger than their present combined areas. Each is destined to grow smaller.

The most common factor that both creates and destroys a lake is a river that carries a great amount of sedimentary material (such as silt) into a basin. Such a river—which was originally the source of the lake—eventually fills it with foreign materials. At first, the river flows rapidly into the lake, and then it slows up. The silt sinks to the bottom, near the mouth of the river, causing the lake to become shallow at one end. The sediments dumped by the stream are porous, and they eventually inundate the water of the lake.

A lake can also be filled in by materials detached from the shores. Such materials are at first held in solution; later, they fall to the bottom as a result of chemical change, or by materials carried by the wind, or by volcanic ash.

THE SEA | graveyard of continents

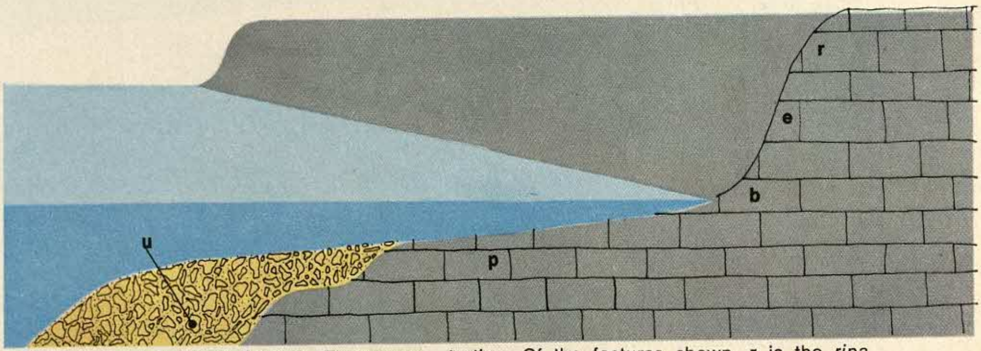
The sea is the graveyard of the continents. The Earth's crust is raised from the depths of the sea to form the continents by orogenesis, and the sea reclaims the land that is worn down and destroyed by erosion. This process has been going on for millions of years, and the land today is the result of an incessant struggle between orogenesis and erosion. But the sea is not only the dumping ground for the sediment of erosion; it is also a powerful agent of erosion and a transporter of materials wrenched from coastlines or washed down by rivers.

Chemical reactions in the sea often lead to the formation of solid material that falls to the bottom and creates enormous quantities of sediments that are of great importance to life. In the last billion years—the period of time for which it is possible to reconstruct the history of the Earth, at least in part—innumerable species of animals and plants have lived in the sea and left their imprint in these sediments. Some of the sediments are now above sea level, forming rocks and mountains, and in these traces of life the story of the past can be read.

Much of the sediment that has been deposited on the seabed has become compact and solid, forming rocks. Over the vast span of geological time, one thick layer of rock has been laid on another by the sedimentation of materials eroded from the surface of landmasses and carried into the sea.

The distance from shore has relatively little to do with determination of sediment types, because tidal currents are often strongest on the outer edge of the continental shelf. Geophysical investigations indicate, though, that the thickness of sediments increases seaward, with up to 20,000 ft of unconsolidated sediments at the edge of the continental shelves. The continental slopes, which begin at the edge of the shelves, also overlie about 20,000 ft of sediments.

1

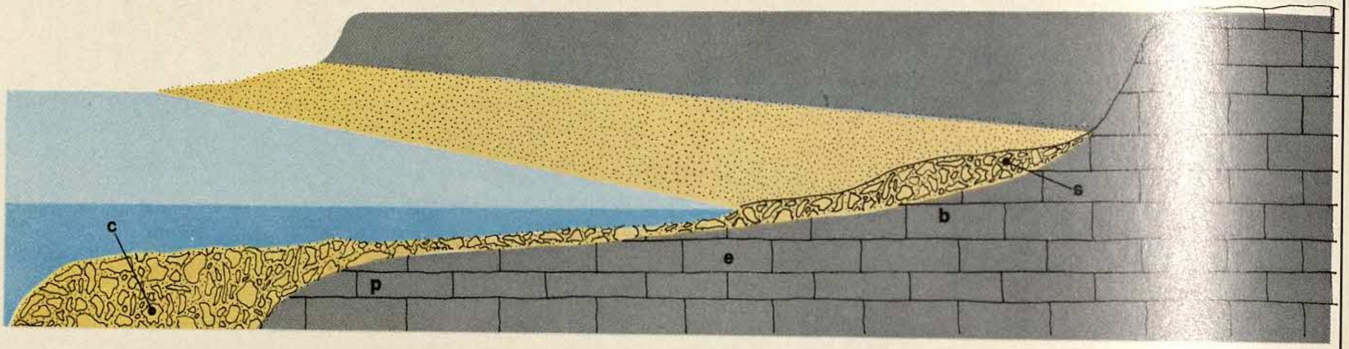


EROSION OF A YOUNG COAST—The waves that beat on the coastlines erode and change them. The continual assault by the sea slowly breaks up the rocks, which then fall into the water. The currents and the waves grind the rocks into small pieces and carry them in suspension far out to sea. The unceasing action of the sea gradually transforms a precipitous coastline into a flat, sandy one. A coast that rises high and almost vertically from the sea is called juvenile. It has existed for only a short time, in terms of the geologic history of the Earth, since it was raised by orogenesis. In this case, a short time may mean as much as several million years. The erosion of juvenile coasts by the sea occurs in a particular way, as explained by the illustration. Of the features shown, **r** is the *ripa marina*, the area of dry land that slopes down toward the sea; **e** is the part of the coast exposed to the action of the waves and, therefore, subject to erosion; **b** is the shoreline; **p** is the offshore shelf formed by deposits of material eroded from the rocky coast and carried out to sea by waves and currents, and **u** is the tip of the shelf. Some distance offshore the shelf takes a sharp dip downward for several yards. Where the seabed begins to dip, the sediment accumulates, forming an extension of the shelf. Farther out the seabed reaches a depth of about 200 m (about 656 ft) and remains at about this depth for some distance from the coast, forming the continental shelf.

2

A JUVENILE COAST—Though most of the Italian Adriatic coast is of the senile type—flat and sandy—this precipitous coast near Ancona is made of easily erodible material. The waves and the agents of erosion in the atmosphere are causing it to crumble slowly into the water. On the beach are chunks that have broken off from the cliffs and will gradually be broken up by the waves and reduced to fine sand that is easily transportable. The beach is always free of sediment; and the coast, as long as it is precipitous, will continue to lose fragments of its rock. The water near the beach is not clear because of the amount of eroded material in suspension.

3

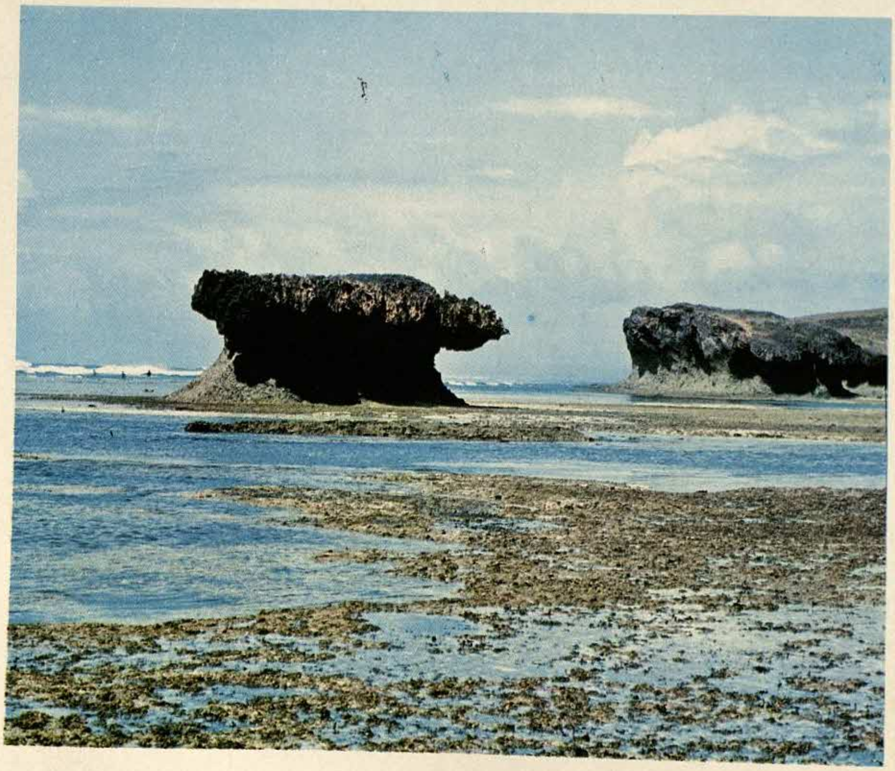


EROSION OF A SENILE COAST—A stretch of coastline that emerged a long time ago, geologically speaking, has undergone extreme changes. No longer does the coastline fall almost vertically into the sea; instead, it is flat and low-lying. The waterline is on a sandy beach, and the seabed slopes away gradually. The bottom is sandy. The waves and currents are continually shifting the sand and slime on the seabed. Any coast of this kind is called a senile coast. In it, **r** is the *ripa marina,* the area of dry land that slopes down toward the sea. It may consist of a low bank, or it might be high and steep, but in this case it will be quite a distance from the waterline. The letter **b** marks the part of the coast continually subject to the action of the waves. In the case of a senile coast, this area is made up mostly of fine materials such as sand. In a juvenile coast area, **b** may consist of a narrow strip of stony beach or even of a cliff that rises almost vertically from the sea.

The edge of the area exposed to the action of the waves is marked **e,** while **p** is the offshore shelf, formed by deposits of sediment from the destruction of rocks or by materials carried by waves and currents. The sediment **s,** on the beach, is composed of pebbles of fine sand. The depth of these sediments varies from one beach to another, and the surface shifts with the action of the waves. The clastic layer of the seaward offshore shelf **c** is composed of materials dragged out from the shore by the waves and currents.

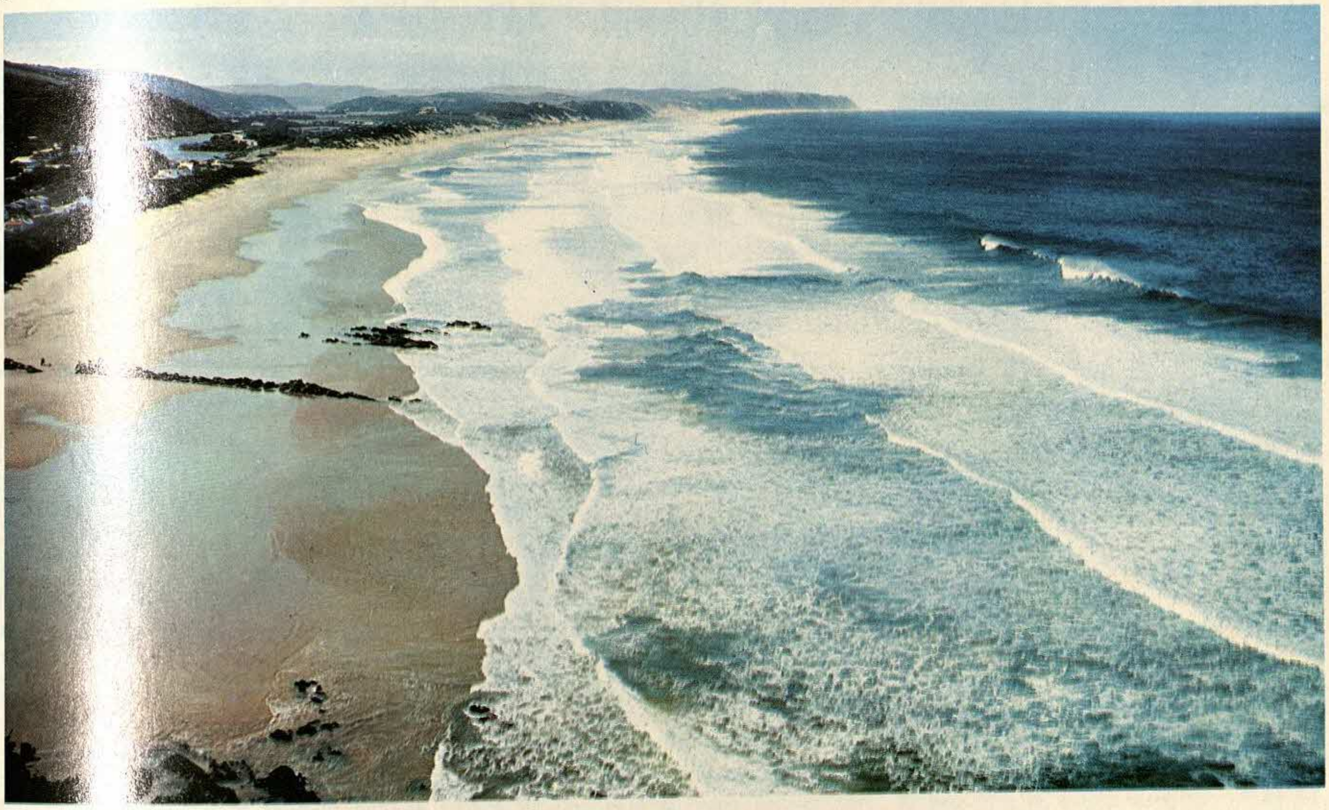
In the area marked **p,** the offshore shelf dips down until it reaches the 100- to 200-m depth (about 328 to 656 ft) of the continental shelf. Here the materials of the clastic layer, carried out by the movement of the water, form a kind of step similar to what is called, in the case of a juvenile coast, the tip of the offshore shelf.

4



THE SELECTIVE EROSION OF THE SEA—When waves break on a beach composed of rock strata, they meet different degrees of resistance from the different kinds of rock, and these rocks are eroded differently. On the illustrated coastline on the Indian Ocean near Malindi (Kenya), the rocks offering the least resistance have been reduced to water level. Rising above these rocks are those rock strata that have greater resistance and have been eroded less by the sea. When the waves strike the less resistant strata, they bite deep into them, and the more resistant rocks take on strange forms. This explains the mushroom-shaped rocks found isolated on beaches otherwise composed of pebbles and sand. These rock formations are more eroded at the base than at the top because the full force of the waves strikes them at the base.

5



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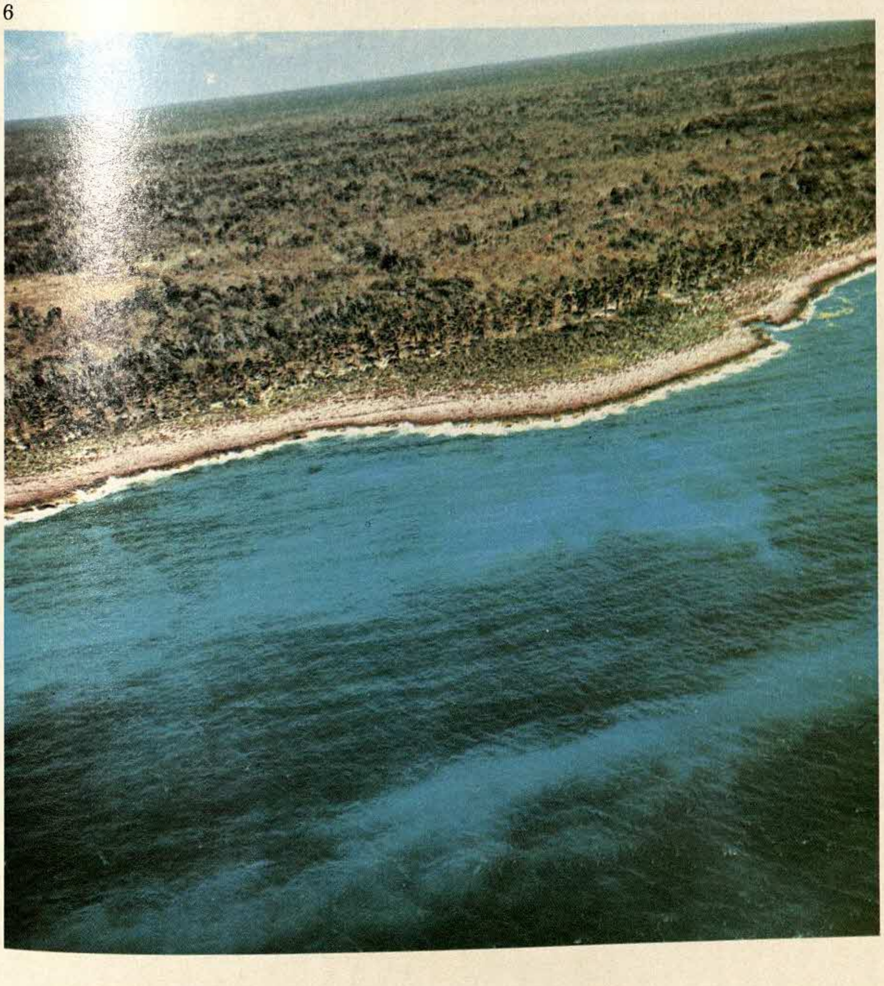


A SENILE COAST—On this low, flat coastline the waves beat on a sandy beach formed of sediment eroded from the coastal escarpment. The constructive and destructive action of the sea is caused by the movement of the waves, which carry with them materials eroded from the coast (if the coast is being destroyed) or deposited by the waters (if the coast is being built up). Near the coastline erosion is most active because the very turbulence of the waves enables them to carry the materials they have eroded. Such water is often cloudy, and this cloudiness is an index of the speed with which material is being carried away and sedimentation is taking place. The farther out to sea, the clearer the water as the action of transport and sedimentation lessens.

Although it might seem that the water is clear only a short distance from the shore, there is an imperceptible amount of turbidity, which is enough to cause a great deal of sedimentation over periods of geologic time.

UNDERWATER LIFE ALONG THE SHORE—On this stretch of Caribbean coast (Quintana Roo), a dense crop of seaweed grows on the underwater sediments. The innumerable species of living creatures that inhabit this seaweed are a rich local fauna. From the coastline outward to the edge of the continental shelf, the seabed is endowed with a seething animal and vegetable life that can often influence the speed of erosion or construction by the sea.

THE SHIFTING OF THE SHORELINE

Man's earliest impression of his planet probably was of a limitless expanse of land broken only here and there by small bodies of water. Many centuries later he thought of Earth as a vast land bordered by water—by a giant river, perhaps. Only very recently—in terms of Earth's geologic age—did man learn that his is a watery planet, with more than two-thirds of its surface covered by water.

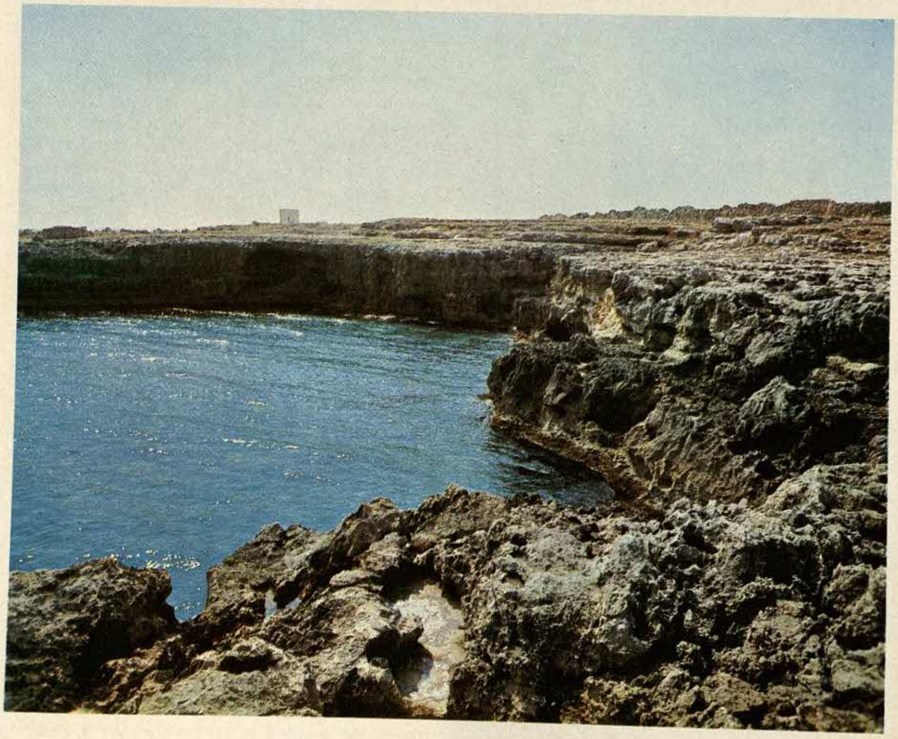
For billions of years the seas have been washing over the Earth, controlling the winds and rainfall. Life was born in the sea and later spread to the land that emerged from the water. The sea is the resting place of the fragments of rock that its waters tear from the land and carry away, sometimes over great distances.

The first men who peered into the underwater world undoubtedly found it foreign to the world they knew. They may have considered the shoreline a stable and eternal boundary between two kingdoms, the land and the sea, without realizing that the Earth is changing constantly. Since the continental landmasses emerged from the seas, the level of the water has changed continually, rising or falling according to the amount of water in the maritime basins. The changing sea level acts in the same way on all the coasts of the world. Movements of landmasses, causing the shoreline to shift, involve particular stretches of coast—for example, one section of the rim of a single continent.

This shifting of shorelines has enabled scientists to find traces of life of remote eras in the marine sediments that have emerged and become rock. These sedimentary rocks were formed in the sea, in the relatively shallow waters of the continental shelves, where a moderate shift in the level changes the shoreline.

COASTAL EROSION—Much of the coast of southern Italy is undergoing a regression, for the entire area is slowly rising. This stretch of coast between Polignano and Bari shows how erosion once flattened out the coast. Then the coast began to rise and became "rejuvenated." Erosion has cut deeply into the rocks to form an almost vertical escarpment.

1



PROOF THAT THE LEVEL OF THE SEA CHANGES

Study of sedimentary rocks and reconstruction of the surroundings in which they were formed are based on research of the exact significance of clues, however slight they may be, that lead back to the origins of life. Proof that coastlines have not always been fixed can be seen in the remains of human culture, buildings, and other man-made objects found at the bottom of the sea. Not far under the surface of the Bay of Douarnenez in Brittany can be seen the remains of the city of Ys, which was submerged in the fifth century A.D. when an exceptionally high tide broke the natural dike that had protected the city. In Italy the remains of Roman towns are found under water, especially in the Adriatic, where the sea has advanced and destroyed them.

At Savona, Italy, is a cave with a high vaulted roof and a deep floor cut by the sea. As much as 20 feet above the present water level in the cave are traces of sea animals (*Lithophagi*). Acid secretions from these animals made holes in the rock. *Lithophagi* do not live above water, so the holes in the rock prove that the water level in the cave was once much higher than it is now. On the floor of the cave, now under water, is evidence of prehistoric human habitation: utensils, fireplaces, bones, and refuse of various kinds. These artifacts show that at some other time the cave was free of water. The changing of the sea level in this case is a rather local phenomenon which took place over a few hundred—at most, a few thousand—miles.

There are also less extreme examples. It is widely known that the coast of Holland is vulnerable to invasion by the sea. The Dutch people have learned to build dikes, at first to protect the coastal regions and more recently to reclaim land under water. Such reclamation is very difficult because the land sinks slowly as it dries.

At Pozzuoli, Italy, near Naples, stands the famous Temple of Serapis. Traces of *Lithophagi* on columns of the temple

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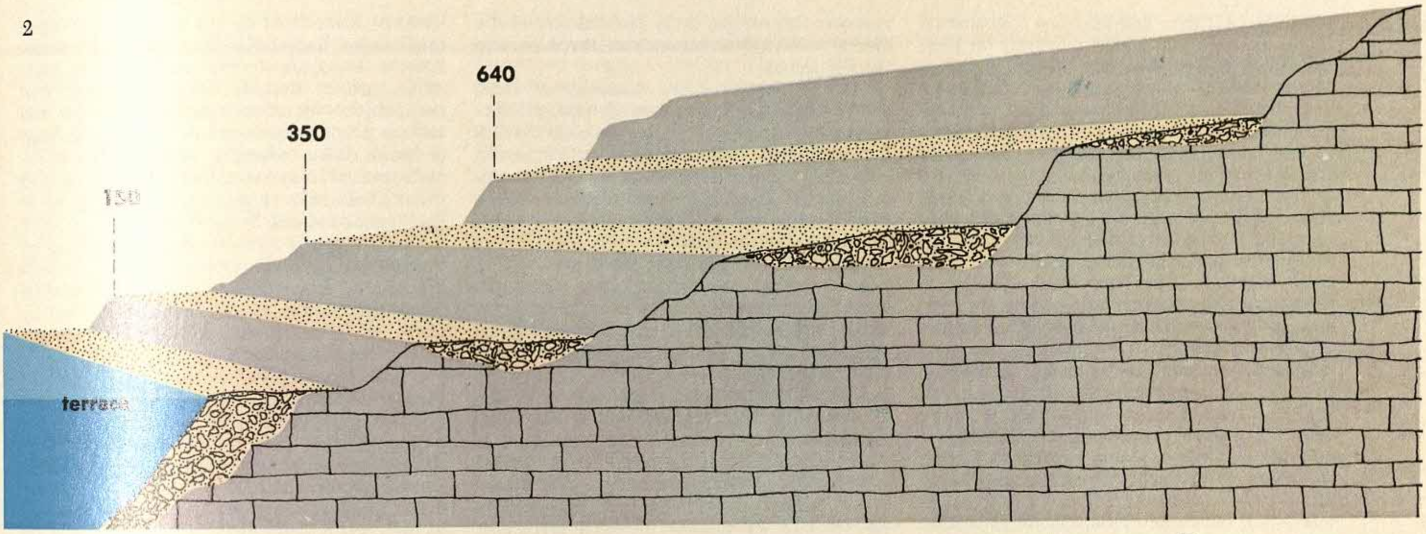

THE UPCAST OF CALABRIA—The coast of Calabria, the "heel" of the Italian peninsula, is slowly rising above sea level. This rise has occurred in a number of stages, as shown by marine sediments that have been deposited inland on a series of terraces, each of which formed the shoreline at one time. The illustration shows a cutaway view of the coast near Catanzaro, where as many as three marine terraces are above the present shoreline. The marine sediments in these terraces are made up of materials which grow progressively finer from landward to seaward. The terraces are 150, 350, and 640 m (about 490, 1,150, and 2,100 ft) above sea level, and bear witness to an extremely rapid rise of the coast—a rise that occurred within the last million years, very recently in geological time.

A MARK LEFT BY THE SEA—This stone clearly shows the holes left by the sea animals, *Lithophagi*. These animals live only under water—proof that the stone was once submerged.

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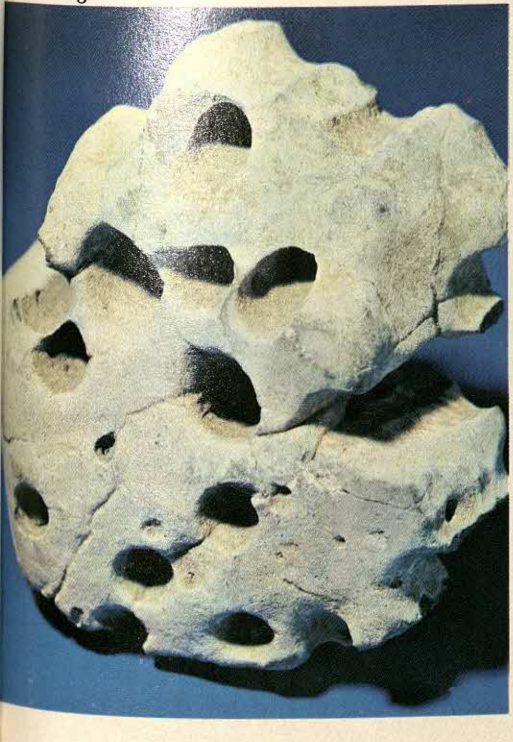

show that it has been submerged in the sea several times and has later reemerged. The cause of the movement is again a local phenomenon, in this case connected with the volcanic nature of the area, and not with a general change of sea level. This phenomenon—bradyseism, or so-called "slow earthquake"—threatened to submerge Pozzuoli and the temple again early in 1970.

Proof of changes of sea level and coastline can be seen also in seabeds where scientists have found the ancient valleys of rivers which now end where the rivers flow into the sea. The valleys and river beds which cut through the land sometimes continue on the bottom of the sea for tens or even hundreds of miles. In these cases the bottom was once dry land, and the rivers cut longer valleys, flowing into the sea much farther out than at present.

Coastal marine sediments have one particular characteristic: near high, young coasts they are made up of rocky fragments varying in size according to how far they are from the coastline. This can easily be seen near such a coast whenever the water is clear. Farther away from the coast, the fragments carried out by the waves and currents decrease in size. In the seawater not far from shore, there is nothing but sand; much farther out, there is only mud. This succession of sediments has such clearly defined characteristics that if found on land there is little danger of confusing them with nonmarine sediments. The presence of marine sediments on land is the most obvious proof that the sea has withdrawn or that the coast has risen. Each continent has at least one wide lowland that has been invaded repeatedly by seas and is now mantled with distinctive marine strata.

Along the east coast of the United States, the sea level has risen at the rate of about 2 ft per century. This is generally attributed to the melting of polar icecaps, which adds water to the ocean. In Scandinavia, however, tide gauges show that the land is rising relative to the water. There the effect is explained as isostatic adjustment—the land had sunk under the weight of the Pleistocene ice sheets and, as the glacier ice gradually receded, the land began to rise back to its previous level.

SEDIMENTATION | all-important key to geological time

SEDIMENTATION ZONES—The illustration shows the basic conditions necessary for sedimentation; it also indicates the properties of rocks that are formed from different types of deposits. On the left are continental deposits, or those that were formed from sedimentation on land above sea level; in the center are deposits of transition, or those that are formed in coastal zones subject to the movements of the sea and that are alternately covered and uncovered by the sea. On the right are marine deposits formed from rock material broken off by the force of the waves, by river sediments carried out to sea by currents, and by the precipitation of substances dissolved in water.

Among the various types of continental sediments, those of volcanic nature produced by the accumulation of scoriae or of ashes thrown up during eruptions are highly important. A classic example of rock having this origin is tuff, which, in rare cases, may contain badly preserved fossils.

Glaciers cause the accumulation of chaotic sediments, called moraines, that may attain massive dimensions, as at the opening of the glacial valleys that slope from the Alps and the Himalayas.

River sediments **a** are made up of sand, gravel, and clay; if they date far enough back they may be cemented by natural binders (often calcium carbonate or, less frequently, silica or dolomite) that infiltrate through various minute openings. These natural binders often contain animal and vegetable remains.

Another typical sediment **b** is made up of the materials that pile up at the foot of slopes; sometimes this debris is composed of large, coarse fragments and sometimes of various-sized, smoothed-down chips, depending on the intensity of the landslide that brought them to the bottom.

Another typical-looking sediment **c** is that formed from materials carried by the wind. These are usually sands, from arid soils in desert climates, that the wind redeposits as dunes. When sands of this type are buried under other kinds of sediments, they can be identified by the manner in which the grains of sand are stratified, by their rounded-off form, or sometimes by the chemical changes they have undergone through long atmospheric exposure before being buried. Another type of deposit consists of very fine particles of morainic rubble blown off the surface of glaciers or moraines. Great masses of these eolian deposits were formed in remote glacial eras, especially in Canada and China. The rocks formed from the material of these deposits are known as loess.

The sediments **d** that gradually build up on the bottom of lakes, slowly filling them until the lake no longer exists, very often make up easily identifiable rocks. They are formed by sandy or clayey sediments deposited in fine, spread-out layers following the topography of the floor of the lake. Similar clay sediments also accumulate at river bends. Such deposits are elongated and curved because they follow the winding of the riverbed. Often lake sediments contain a fossil of flora and fauna of a particular type. Chemical processes working to dissolve rocks may cause the formation of particular sediments or incrustations in the case where dissolved materials are rede-

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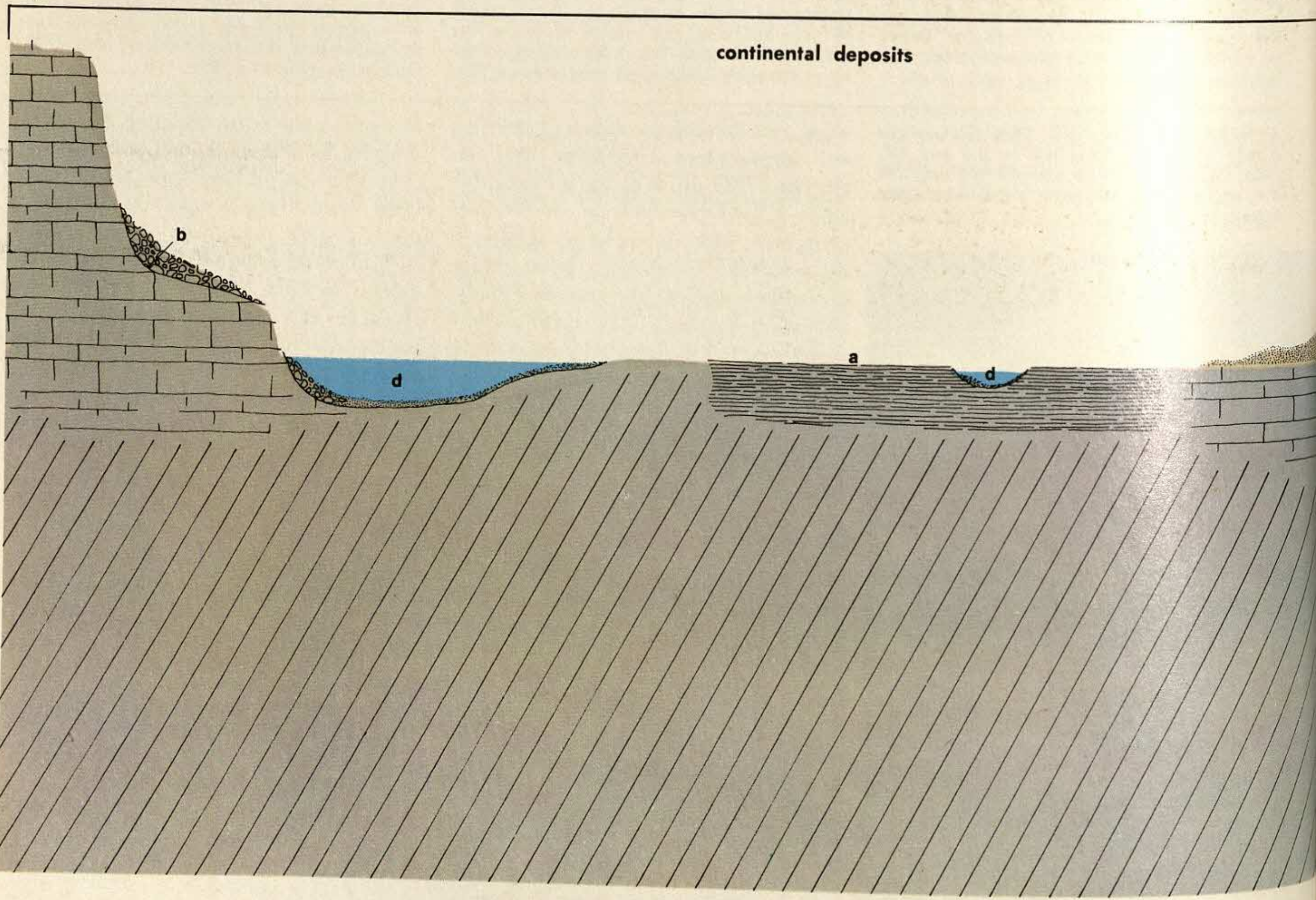


posited; this occurs in grottoes with calcareous coatings, and at the outlets of hot springs. Often the silica or limestone dissolved in such springs is deposited to form rocks, which are sometimes transparent and variegated (onyx) and sometimes opaque and compact (travertine). Surface alterations due to atmospheric agents may also cause the formation of loose materials that, when carried away by wind or water, build up, forming sediments of the alteration type. A typical example is a deposit of bauxite cement; many red clays also fall under this heading.

In many coastal zones, the lowlands **e** stretching inland are not far above sea level. Frequent invasions of seawater or fresh water may cause a special type of sediment to form. Sediments of a particular character, such as those forming the floor of a lagoon, may be deposited. Due to the abundance of peat formations, lagoons often contain carbon-rich sediments. Coastal lowlands are inundated with sediments of a composition determined by the salt content of the seawater from which the sediments emerged. Therefore, these deposits may contain more or less salt and fossils of species determined by the original organism's adaptation to life in fresh, salt, or brackish waters.

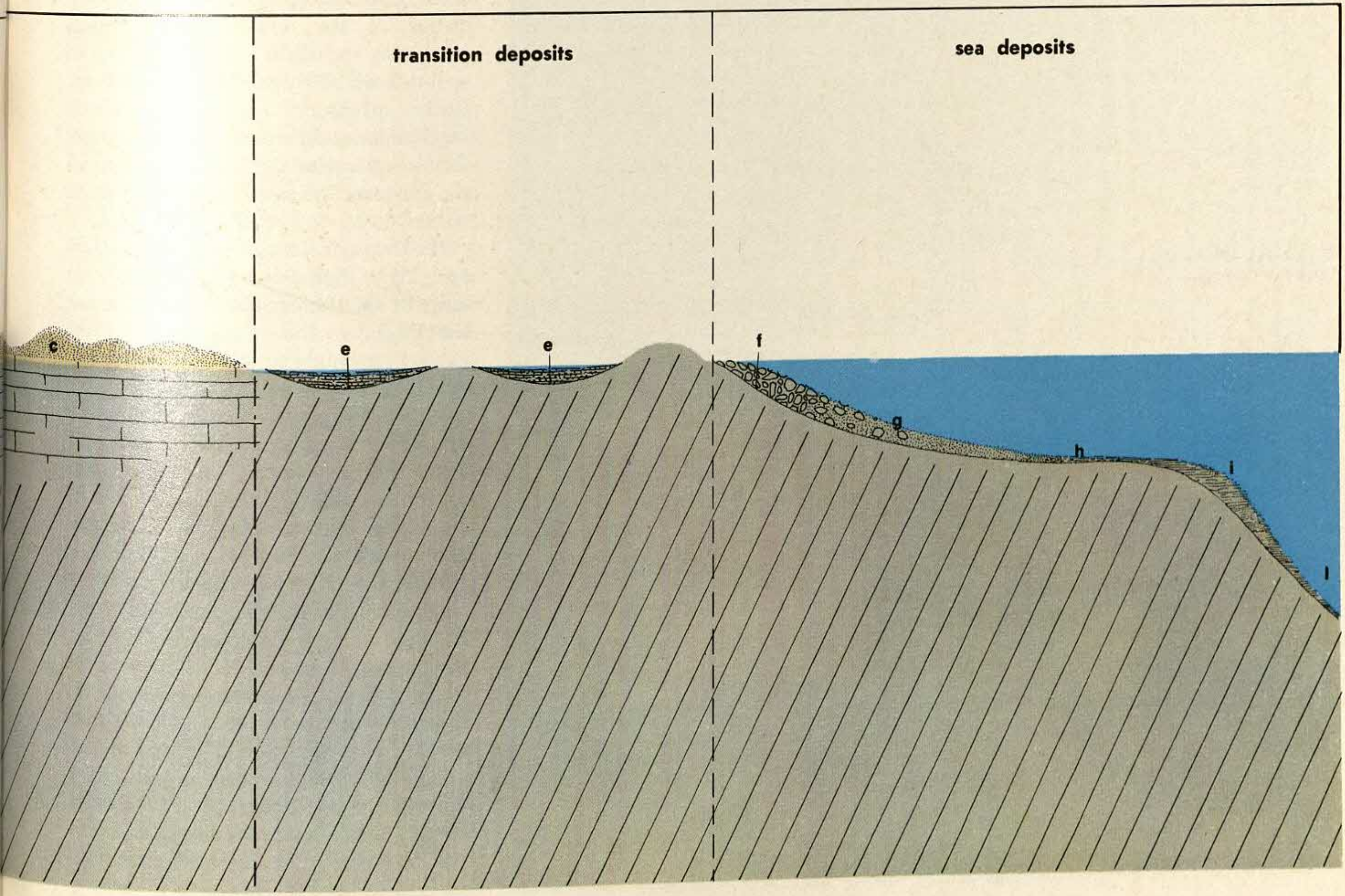
River deltas produce special sediments that extend beyond the coastline into open sea **f**. These sediments are formed by alternating strata of fine and coarse materials distributed according to the flooding cycle of the river that carried them out. They are often rich in animal and vegetable fossils.

Sediments that form just off the shoreline **g** along the coast are called littoral deposits. If the coastlands are low, these deposits are generally made up of fine sands and slime. If the coastline is high and rocky, sediments are often formed from coarse materials (gravels). These sediments often harden around fossils of species living along the coast and in shallow water.

Sediments that form at depths **h** up to 200m (about 650 ft) are called neritic. They are characterized by sands and sometimes shale, and they enclose innumerable remains of vegetable and animal fossils common to this zone, which corresponds to the continental shelf.

The so-called deep-sea or bathyal sediments form at greater depths **i**, between 200 and 3,000 m (about 650 to 9,800 ft). Since water this deep is found in zones far off the coast, the weak currents at these depths transport only extremely fine slimes and clays that solidify in time into highly compact and homogeneous rocks. The clays in ocean sediments tend to resemble those of the nearest land sources. Fossils in the bathyal zone differ from the neritic.

Far from the continental shelf **j**, marine sediments form very slowly. Their sources have not been completely identified; sea currents carry only a minimum amount of materials away from the coast or from dry land. Most of the materials that contribute to the abyssal facies come from particles of skeletons of minute organisms known as plankton; about the same amount probably comes from volcanic and meteorite dust. In any case, sedimentation in these zones occurs more slowly than in the neritic and bathyal zones.



Throughout the geological eras of the distant past, the sea rolled back and forth over almost the entire surface of every continent on the Earth. Some regions underwent flooding only once or twice; others were inundated many times. Today, the history of these ebbs and flows of the sea can be completely reconstructed by analysis of the rocks that were formed during these cycles.

The remains or traces of once-living organisms of aeons ago, or the actual animals or plants themselves, are called fossils. They are found in the sediments that formed on the surface of the Earth's crust. In any study of the history of the appearance and evolution of life on the Earth, fossil evidence is vitally important.

Almost all forms of life have undergone a complex evolution. By studying different species of fossils, geologists characterize the various rocks and the epochs during which they formed. Fossils in a given rock make it possible to determine the relative age of the rock and also to reconstruct the physical characteristics surrounding and contributing to its formation.

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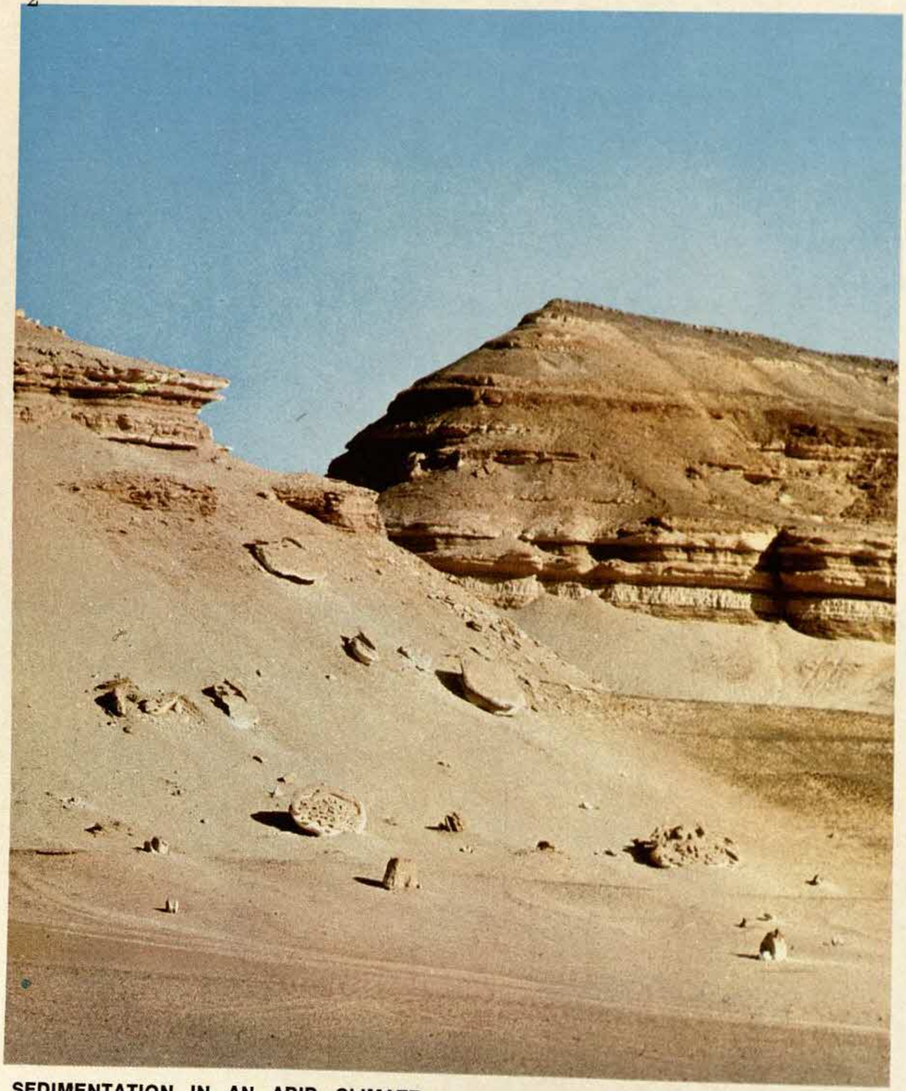


SEDIMENTATION IN AN ARID CLIMATE—Atmospheric causes of erosion, along with the force of gravity, form sediments made up of coarse rocks on the mountain tops and of material that becomes progressively finer as it descends, as here at Zelten, Liberia. Downhill creep operates on any slope covered with loose, weathered material.

FACIES AND FORMATION

If a portion of the Earth's crust—as, for example, the crust forming the bottom of the Mediterranean Sea—should rise until it emerged completely above the water, the soil of the newly formed region would be made up of rocks formed from the sediments deposited on the sea floor over an enormous span of time. Most of the sediments that have actually settled in the Mediterranean, particularly those that have accumulated in its deepest parts, have a characteristic and quite similar appearance.

This resemblance is due both to the extremely similar nature of the solid particles deposited and to the constant association of the remains of organisms (skeletons and shells) that have lived in well-defined environmental conditions. Rocks exhibiting such characteristics would appear different from those found if the bottoms of the Gulf of Mexico or the Caspian Sea should rise above their waters.

Rock masses that have the same origin are called formations. They may cover large or small areas; for example, where the Urals are today, an enormous sea existed for hundreds of millions of years. The sediments from this sea made up an enormous formation. Even the sediments of a lake, during its brief life, may lead to the creation of a small formation. The types of fossils included in these sediments, the mineralogical characteristics of the rock, the conditions under which the rock was deposited—all make up what geologists call the facies (from the Latin word meaning "face" or "aspect") of the rock formation. Knowledge of the facies makes possible identification of the type of environment in which the rock was formed. Minerals, which occur naturally and are generally inorganic, are the basic units that compose most rocks. Certain minerals are associated with certain kinds of rocks. To geologists, minerals are a kind of alphabet.

DATING ANCIENT ROCK STRATA

The rocks of the Earth have often been likened to a book containing the history of the Earth. Among the principal subjects of this "book" are strata, or layers, of sedimentary rock, the fossils embedded in these rocks, and the evidence of chemical and physical changes that have occurred in the rocks.

By studying rock formations and the fossils within them, geologists can read the story of the formation and wearing down of mountain ranges, the drifting of continents, the rising and falling of sea levels, and the evolution of living things on Earth. Before they can determine the sequence of events that occurred during the Earth's past, however, geologists must know the relative age of the rocks they are studying.

SEDIMENTATION ORDER

One of the oldest and simplest methods of determining the relative age of sedimentary rocks is merely observing the order in which the rock strata occur. The uppermost layer was usually formed last and is the youngest layer in a series; the lowest layer is the oldest. No absolute ages can be assigned by this method, however, and the method is not always accurate in terms of relative age. Over millions of years the once-horizontal strata may have warped and folded over on themselves; this can lead to errors in determining relative ages, for older rocks may lie above younger ones. The geologist may have to trace strata over large areas to determine if he is examining a reversed series.

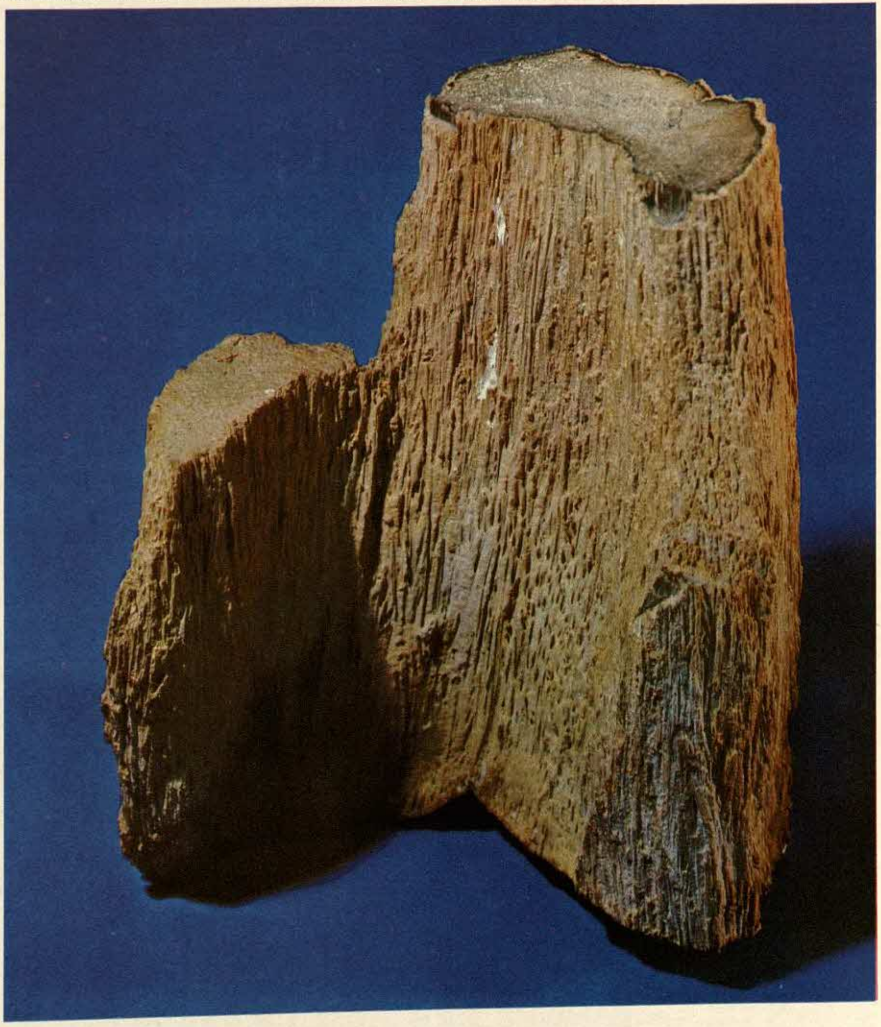
The thickness of a stratum of sedimentary rock is not an accurate clue as to the length of time required to form that stratum. Different kinds of sedimentary rocks form at different rates in different parts of the world. For example, it is possible for thick layers of sediment to accumulate in a short time near the mouth of a river, while extremely long periods of time may be required for the formation of a thin layer of sediment in the abyssal regions of the ocean.

FOSSILS AND DATING OF ROCK

Early in the nineteenth century, geologists discovered that fossils of some species of plants and animals were found only in certain strata. In some cases there was a gradual change, or succession, in the types of fossils from the oldest strata to the youngest strata in a particular location. Because of this, it has been possible to correlate some fossil species with strata of known relative ages. As a result, the relative age of certain rock samples may be determined by identifying the fossils it contains.

This method, of course, cannot be applied to rocks that bear no fossils. These

A PLANT FOSSIL—The tissues in this portion of a palm tree trunk were replaced by silica in a process called petrifaction. This fossil was discovered in the arid sands of the Libyan Desert; its presence there testifies to the existence of a wetter climate at some time in the geological past, when humid phases alternated with arid periods.



include igneous rocks (those that once were in a molten state and, therefore, probably never contained any fossils), most metamorphic rocks (those that have been altered by great heat or great pressure that would be likely to destroy any fossils they contained), and rocks formed before life appeared on the Earth. The Earth is believed to have existed for 4.5 billion years, and the oldest organisms for which fossil evidence exists lived about 2 billion years ago. However, reliable estimates of the ages of rocks can be made only from fossils of more recent times—those that lived no earlier than about 600 million years ago.

In addition to their value in determining the age of rock strata, fossils give some indication of the climatic conditions that existed when and where they lived. The remains of a delicate fern, for example, indicate a warm climate, while the bones of a woolly mammoth indicate a colder climate. The remains of fish and other aquatic animals show that oceans, lakes, or streams once occupied the area in which the fossils were found. Only land near or above sea level would yield tree fossils. The presence of marine fossils high in the mountains once puzzled geologists, but now it is known that the strata in which such fossils occur were formed at the bottom of the sea and were later raised to their present position by powerful mountain-forming forces.

RADIOACTIVITY AND DATING OF ROCK

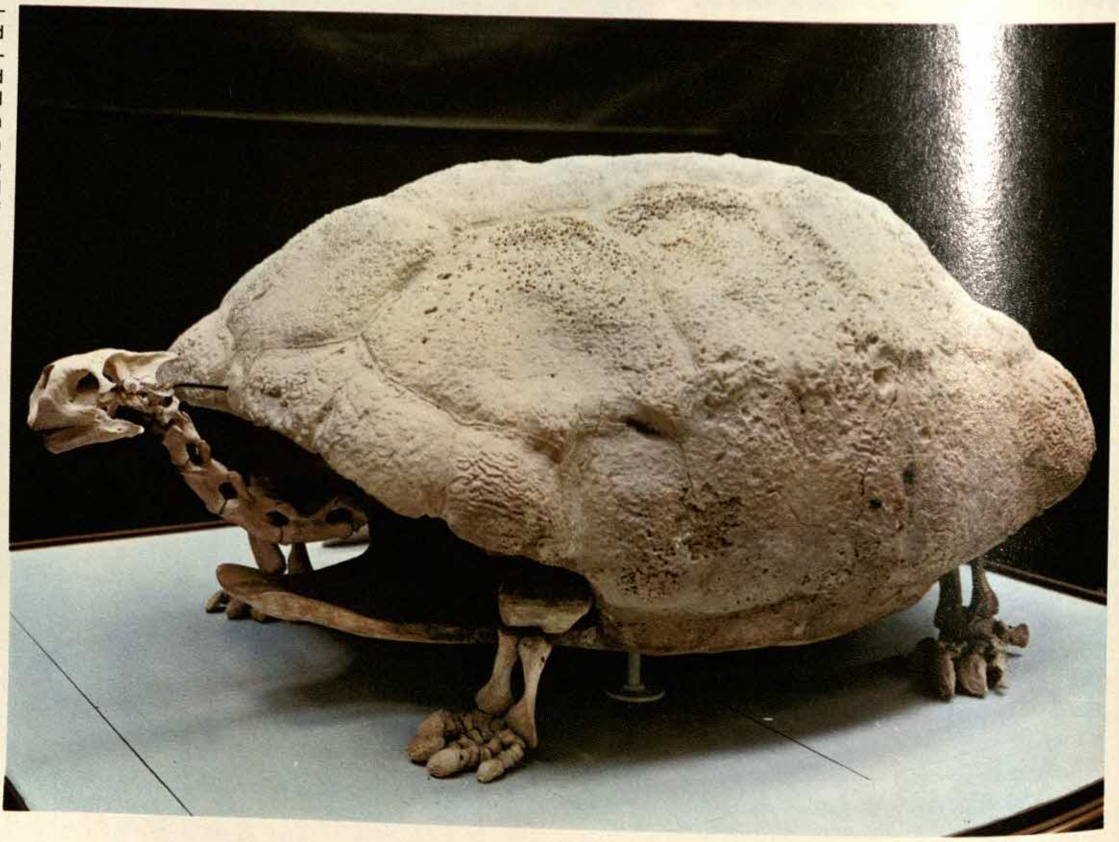
Among the substances of which rocks are composed may be several radioactive elements—elements that are unstable and decompose into other elements. For example, uranium-238 decomposes to lead-206; rubidium-87 breaks down to strontium-87; and potassium-40 forms argon-40. The rate at which a radioactive element disintegrates is constant for that element and is not influenced by temperature, pressure, or other factors. By comparing the amount of the parent element with the amount of the daughter product in a rock, the age of the sample can be estimated with fair accuracy.

A small percentage of the carbon dioxide used by plants in photosynthesis contains carbon-14, which becomes incorporated into the plants and into the bodies of the animals that eat the plants (and eventually disintegrates into nitrogen-14). Measurement of the concentration of carbon-14 in a fossil reveals the age of the fossil and of the rock strata in which it was found.

Radioactive dating has the advantage of giving absolute ages rather than relative ages; however, sufficient quantities of both the radioactive element and its daughter product must be present for accurate measurement. One disadvantage of radioactive dating is that the rock may have contained significant quantities of the daughter product at the time of its formation. Since the daughter product did not result from the disintegration of the radioactive element, errors in calculation are possible.

None of these methods is suitable for every rock-dating problem. In practice, only one method may be used in a particular situation.

AN EXTINCT REPTILE—This giant tortoise, found in Madagascar, is remarkably well preserved for so large a fossil. Good preservation is much more likely to occur with smaller organisms. Some plants and animals lived during just one period of geologic time. The presence of their fossils in a rock stratum reveals the relative age of the rock.



THE DATING OF ROCKS | an atomic clock

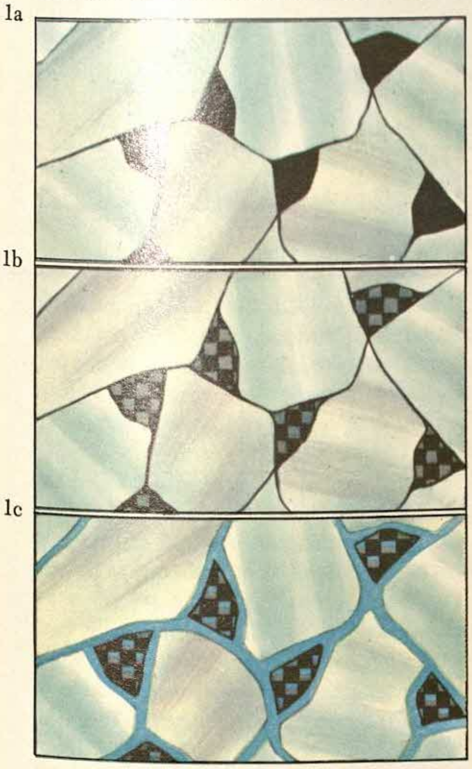
The chronology of the Earth depends essentially on establishing the age of rocks, which are the most durable—and therefore the oldest—of its components. Rocks are constantly being formed by the solidification of igneous molten material (magma) deep below the Earth's crust, or as lava on its surface, and by the hardening of sedimentary material. This solidification has been going on ever since the planet was formed.

To determine the relative dates of rocks (which rocks are older or younger than others) geologists have developed the science of geochronology. More recently, they have devised methods to determine the absolute age of rocks in years—or, at least, in millions of years. These methods are based on the relative abundance in the Earth's crust of such elements as uranium and lead, thorium and lead, pairs of rubidium and strontium, and potassium and argon. This article describes the method based on the relative uranium and lead content of rock.

THE URANIUM-LEAD METHOD

Because uranium is a radioactive element, the nuclei of its atoms disintegrate at a constant rate over long periods of time, emitting alpha particles—two protons and two neutrons—that are identical in composition to the nuclei of helium. When uranium-238 loses an alpha particle—four units of mass and two positive charges—it changes into another element, thorium-234. This isotope also has an unstable nucleus and soon disintegrates into another unstable element. After a series of such disintegrations, the final, stable end-result is lead-206. This entire process of disintegration transforms half of any original quantity of uranium-238 into lead-206 in about 4.5 billion years; or, as scientists prefer to phrase it, uranium-238 has a half-life of 4.5 billion years.

Now, if igneous rock, when it first solidified out of magma, contained any amount of uranium-238 (either pure or in an ore), the process of disintegration would immediately begin, and after 4.5 billion years half the uranium would become lead. It follows that if a specimen of rock is examined and is found to contain as much uranium-238 as lead-206, that specimen is 4.5 billion years old; if it contains a greater proportion of uranium than lead, it is younger than this; if it contains more lead than uranium, it is older. Inasmuch as no rock older than 4.5 billion years has yet been found, all rock containing the two elements has a greater proportion of uranium; but the magnitude of that proportion indicates its age: the more uranium (in proportion



IMAGINARY REJUVENATION—When a rock forms, pure pitchblende uraninite (U_3O_8, Illustration 1a) is isolated. After a time—in this case, some 2 billion years—about half the uranium is turned to lead (Illustration 1b). Some of the lead is dissolved by water (blue in the gray squares, Illustration 1c), altering the uranium-lead ratio so that the date of the rock cannot be accurately determined.

PITCHBLENDE—NUCLEAR CHRONOMETER—By carefully measuring the percentage of lead atoms in this specimen of pitchblende, and the ratio between these and the remaining uranium atoms, it is possible to determine the age of the crystal itself, the rock in which it appears, and even the formation in which the rock was found.

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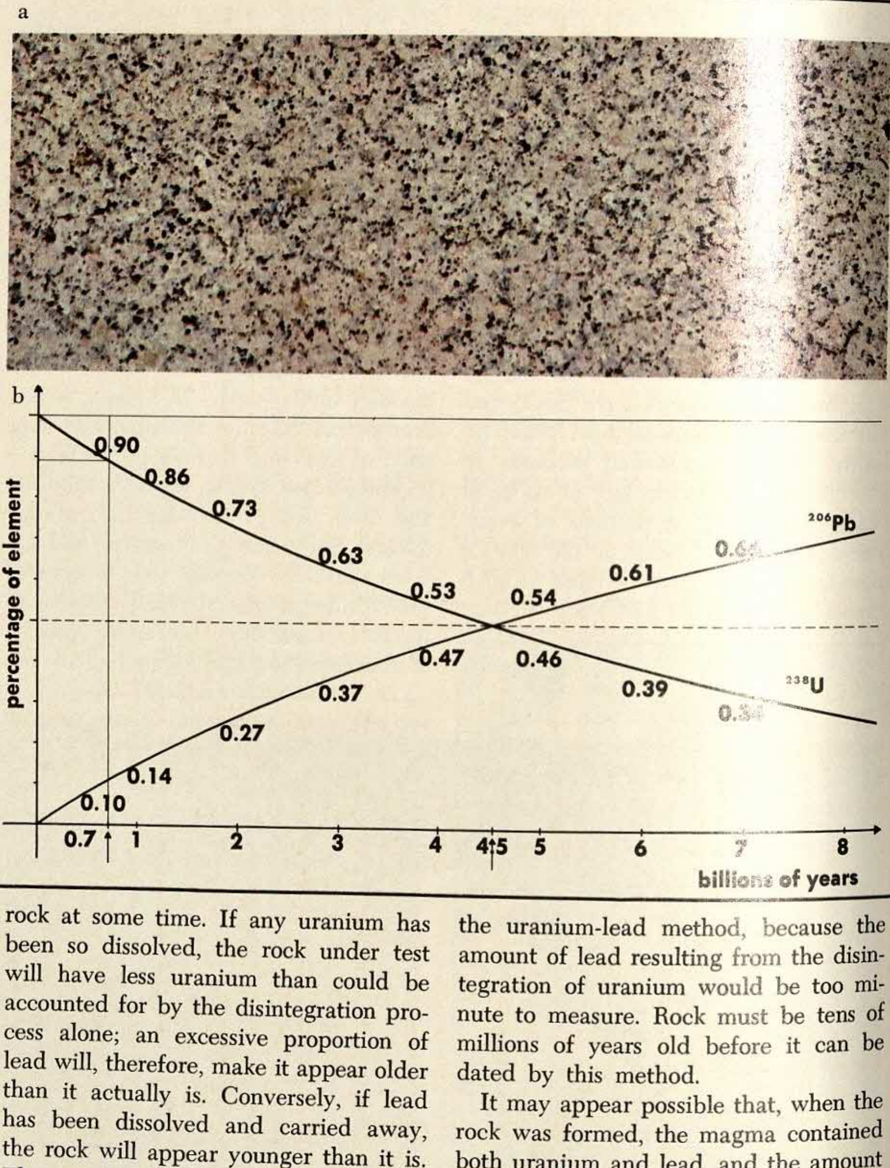

URANIUM-LEAD CHRONOMETER—These illustrations show the application of the uranium-lead method of dating. A rock sample (Illustration 3a), of a size suitable for laboratory analysis, is placed in a mass spectrograph (Illustration 3c), and the lines for uranium-238 and lead-206 are measured to determine the proportion of intensity for each. The graph in Illustration 3b shows the length of time since the uranium began to disintegrate, as determined by the uranium-lead ratio; in this sample, the age of 700 million years is indicated. This illustrates the general principle behind the method of dating according to the radioactive disintegration of uranium; more precise methods are used in practice to date both recent and even older rocks.

to lead), the younger the rock. In other words, the uranium-lead ratio is an age-index of the rock.

LIMITATIONS OF THE URANIUM-LEAD METHOD

Once the presence of lead-206 has been established spectrographically in a rock, chemical analysis will reveal the uranium-lead ratio and thus the age of the rock—within certain limitations.

One limitation is the possibility that either the uranium or the lead or both might to some degree have been dissolved in water that may have come in contact with the rock or been inside the rock at some time. If any uranium has been so dissolved, the rock under test will have less uranium than could be accounted for by the disintegration process alone; an excessive proportion of lead will, therefore, make it appear older than it actually is. Conversely, if lead has been dissolved and carried away, the rock will appear younger than it is. The uranium-lead method of dating is inaccurate, therefore, if there is any sign that the rock has come into contact with water. The method obviously cannot be used for sedimentary rock, which has (by definition) come into contact with water.

Finally, if a rock is very young (in geological terms), it cannot be dated by the uranium-lead method, because the amount of lead resulting from the disintegration of uranium would be too minute to measure. Rock must be tens of millions of years old before it can be dated by this method.

It may appear possible that, when the rock was formed, the magma contained both uranium and lead, and the amount of original lead may be confused with the lead formed after solidification by the disintegration of uranium. This confusion is not possible, however, because when magma solidifies, uranium concentrates into one type of crystal and lead into another type, because of the different ionic properties of the two elements;

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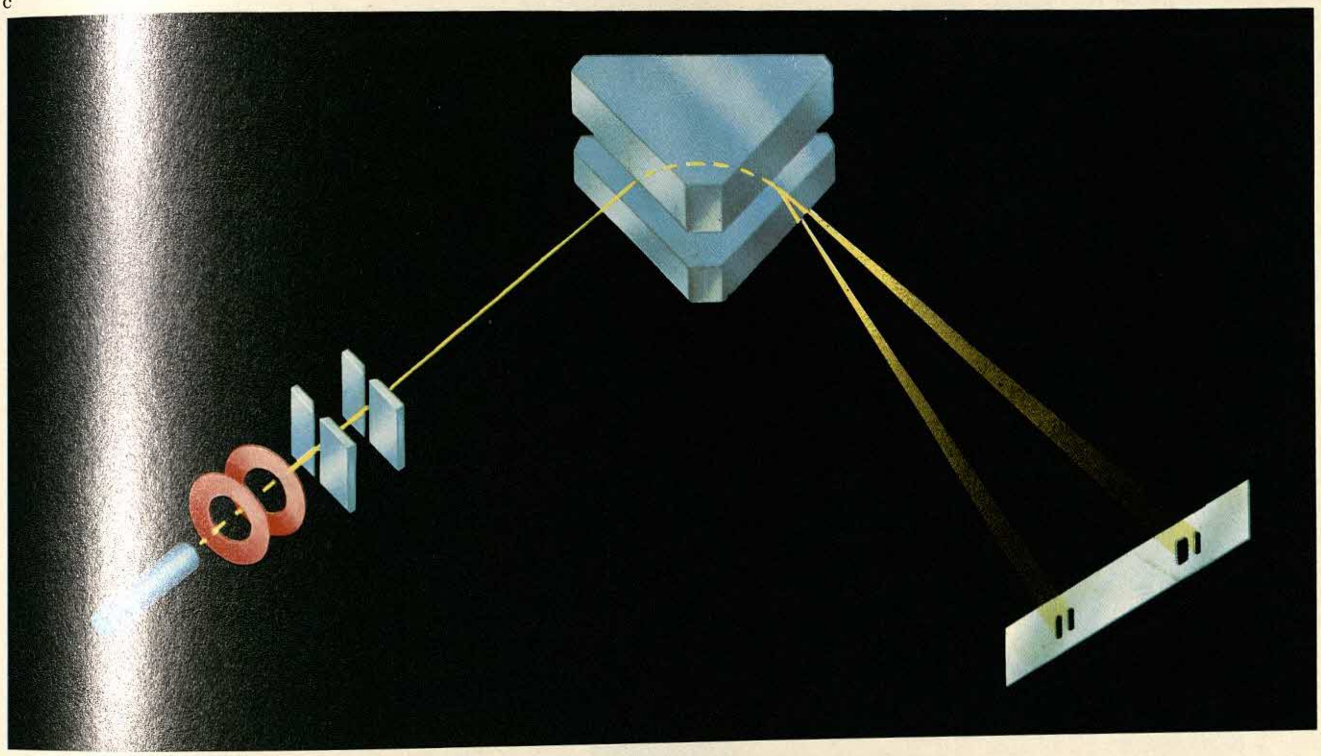


crystals containing uranium will not contain original lead. Therefore, if a uranium crystal does contain lead, this lead was undoubtedly formed as a result of the disintegration of the uranium.

THE OLDEST ROCKS

A specimen to be tested to establish the age of the formation in which it occurs must be studied carefully, not only in itself, but also in relation to the formation. It is best if several specimens from the same formation can be studied comparatively.

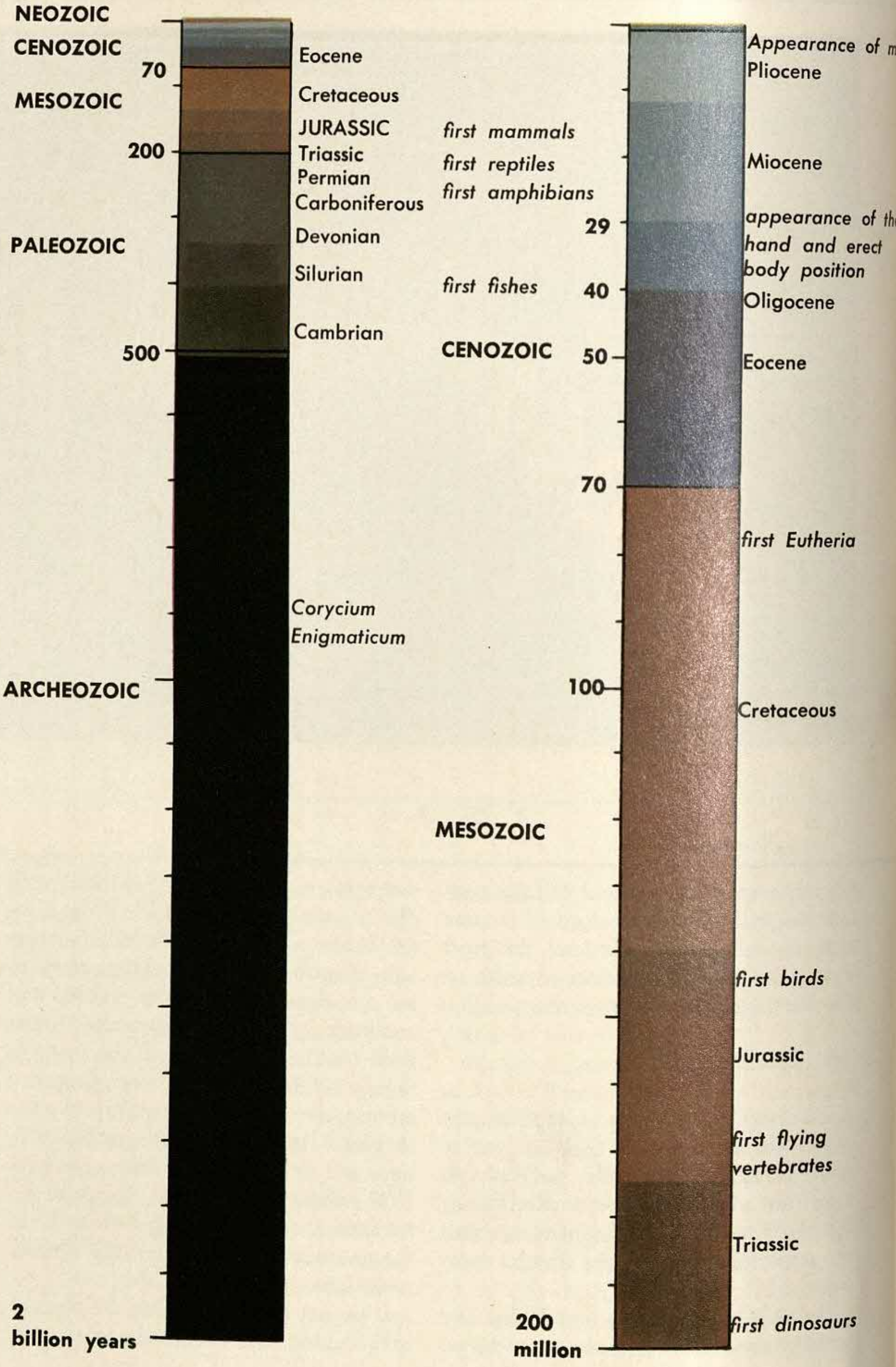
If, for example, it is found that the igneous rock forming a pluton (a large, deep-seated rock) is 250 million years old—in other words, that the magma solidified into a pluton 250 million years ago—then the rocks surrounding the pluton are, depending on their position and condition, either older or younger: older if the pluton intruded into them; younger if they solidified later or were deposited around the pluton. Chronological relationships between adjacent rock formations are determined in this way. Since 1930, when scientists first began to determine the absolute age of rock by the uranium-lead method, many igneous rocks have been dated.

It cannot be stated conclusively which is the oldest rock on Earth. In the first place, dating is necessarily restricted to actual specimens, and only plutons that appear on the surface can be used; those still within the crust or even at greater depths cannot be tested for their uranium-lead content. So far, the most ancient rocks at the surface are the granites in the Republic of the Congo in Africa, at a place known as Shinkolobwe in Katanga, noted for its production of uranium ore. Formations there are about 3.49 billion years old. The chronology of more recent rocks, especially those contemporaneous with life and therefore fossiliferous, is determined by methods other than the uranium-lead method. Radiocarbon dating is one.

CHRONOLOGY | geological and biological history of the earth

Reconstruction of the history of the Earth's crust and of the evolution of life by means of stratigraphic research, based on the traces found in progressively deeper layers of rock, is a major scientific conquest. It is a highly detailed history in comparison with what is known about the events that took place at the beginning of the Earth's formation. The condensation of the planet from solar gases, the solidification of the Earth's crust, and the formation of the atmosphere and of the oceans were cataclysmic evolutions that can be described only through theories based on conjecture. It can be said, for example, that at some point in the Earth's beginnings water vapor began to condense, forming oceans, but it is not known exactly when this occurred, nor are there any known rocks that contain traces of this period of the Earth's evolution.

Likewise, little is known of any of the other events of these primordial "birth pangs" of the Earth. Consequently, it is difficult to name the order in which these



ABSOLUTE CHRONOLOGY—The five columns, reading from bottom up, represent the passing of geological time. The first column, on the left, shows all the eras, while the others are one-tenth of the preceding column enlarged ten times to allow a more precise look at the chronological succession of the events which took place during each period. The first column on the left is a scale of the last two billion years. The history of the Earth's crust, however, is much more ancient, extending back at least three billion years. Since the remains of the most ancient living organisms ever found in the rocks trace back to the beginning of this remote era, it is therefore reasonable to begin the history of the Earth at this date. The preceding events—the formation of the planet, its solidification, and the formation of seas and the atmosphere—still cannot be historically measured.

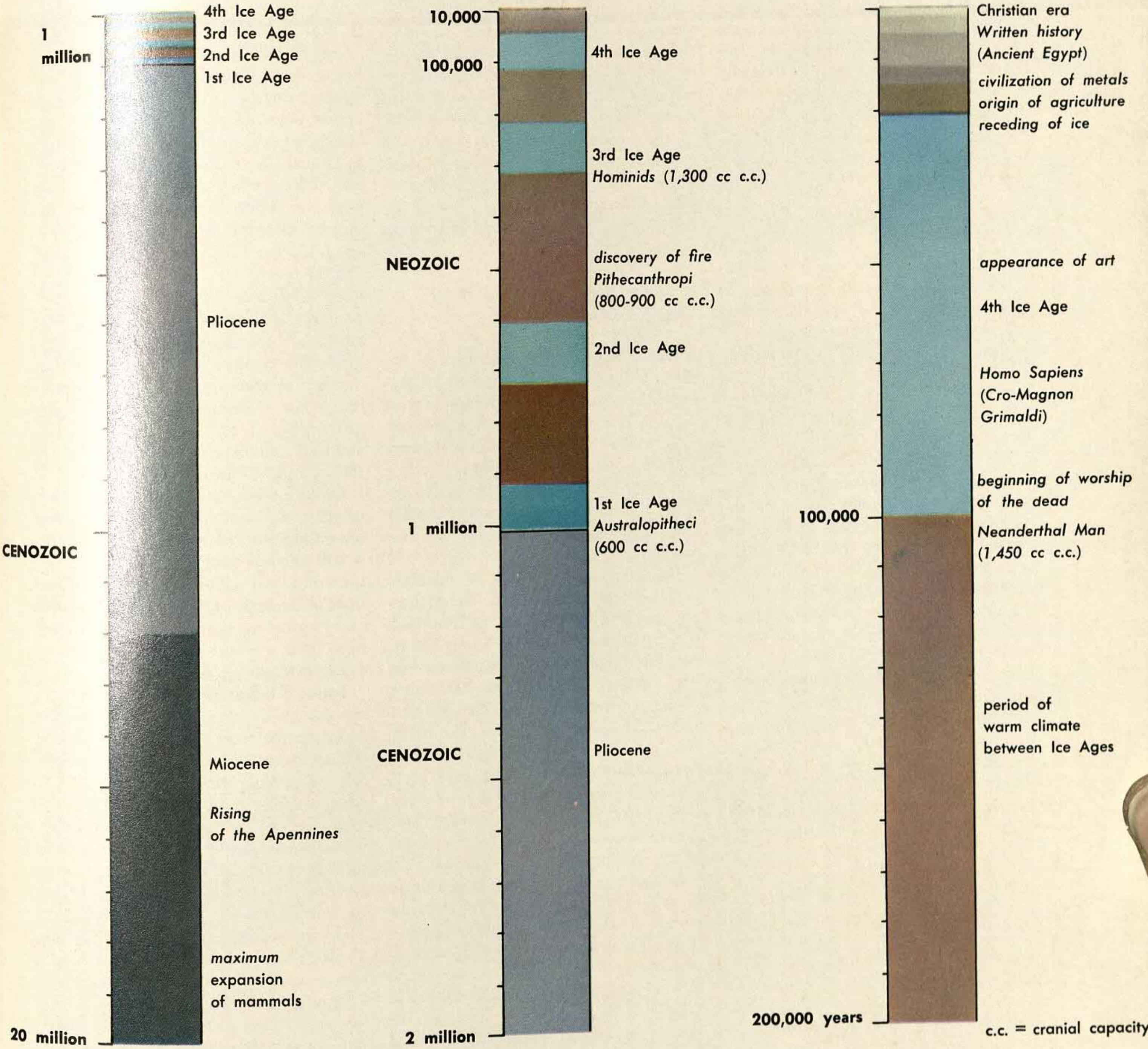
Three quarters of the initial period of the Earth's geological history belongs to the era in which life has left only a few faint traces of itself in the sedimentary rocks. Thus, much of the history of its evolution must be left to supposition.

Another portion of the Earth's history (about a sixth) belongs to the era in which more complex life-forms evolved and, after having conquered the seas, became masters of the dry land. But dates still are uncertain. Many of the rocks formed in this period subsequently were altered by the physical and chemical transformations of later epochs.

In the Mesozoic era, whose length represents a fifteenth of the Earth's geological history, terrestrial living organisms underwent great development. Some of them, belonging to the group of reptiles (Sauria), became enormous and conquered the Earth. Then, without warning, they disappeared. The first mammals also appeared in this era.

The Cenozoic era, in which the mammals conquered the Earth after the disappearance of the Sauria, lasted only about a hundredth of the total time represented in the column. The Neozoic era, in which man made his appearance, lasted only a million years. On the scale of time shown on the far left, it is represented by a thin horizontal line whose width is exaggerated in that it equals one two-thousandth of the height of the column, or one tenth of a millimeter.

The second column represents the last two hundred million years expanded ten times. The Neozoic and Quaternary eras expand to a millimeter of their lengths, meaning that it still is not possible to read temporal subdivisions on these sections. The third column treats the subdivision of the last twenty million years. The huge divisions of the final period of the Mesozoic era are not repeated;



but now it is possible to see the position in time of the Quaternary ice ages, contemporary to the appearance of man.

The fourth column contains a well-expanded view of the subdivision of the Quaternary era, which has lasted a million years. In spite of the enormous enlarging, it still is an insufficient scale for showing in its subdivisions the creation of modern civilization. The fifth column, therefore, must be enlarged another ten times so that the span of time within which written history is recorded can be illustrated.

These five columns, representing the story of the Earth's crust and the evolution of life, give the student a chance to observe the large gap in particulars that exists between the history of the Earth in recent eras and that of events that took place in long-past eras. If we had the same abundance of particulars on the remote eras as we have on the Neozoic era, the story of the Earth's history would require a gigantic library just to hold the most important data of the chronology. In the most ancient eras the progress of life also was much slower; it took billions of years for the first living beings to conquer the dry land after having been born in the seas. At the same time, the movements of the Earth's crust—ice ages, erosion, volcanic eruptions, and other drastic changes—were occurring constantly. As a result, almost all traces of many of the most ancient events have been lost.

events took place or to specify which ones really did occur. It is, however, possible to trace the geological and biological history of the Earth for at least some three billion years. Although the language used by the sciences to classify the Earth's evolutionary cycles is rather difficult at times, the history of these geological and biological periods is possibly even more interesting than the history of humanity.

ABSOLUTE CHRONOLOGY

Today, modern science makes it possible to construct an absolute chronology of geological events. To fully understand and appreciate this history, however, it is first necessary to study the chronological succession of geological events, learning not just the names of the periods but their durations as they go backward from the present day.

Just as the story of humanity is necessarily condensed and summarized when it deals with the distant past (yet minutely detailed as regards more recent events), the story of the Earth suffers from the same defect—to an even larger degree. The scales of geological time in the chart shown are mainly empty, and this emptiness represents the eras deepest in the past. Thus, in order to represent in reasonable detail the more recent happenings, it is necessary to increase the scale of times way out of proportion. The scale, as illustrated, is an outline of the absolute chronology of the Earth's history. The scale shows the length of the geological periods that represent, with their passing, the history of the Earth. A study of the history of each of these periods shows, for example, that in the distant past the Earth's landmasses and seas were distributed differently than they are today. Even the volcanoes were located on different parts of the Earth, with periods of extreme activity followed by periods of dormancy. This study shows that orogenesis and erosion have more than once raised and flattened massive mountain chains. The Alps of Europe, the Rocky Mountains of North America, and the Himalayas of Asia have, for example, risen comparatively recently in the scale of geological history. In other words, the present-day physical geography of the globe is just one brief frame of a long film that can be seen in its entirety only through difficult and partial reconstruction of the past. From this reconstruction emerges the stark drama of the evolution of life on Earth—the conquest of the seawaters, the dry land, and the air as progressively more complex life-forms struggled to adapt to the difficult conditions of survival on an ever-changing planet.

THE ENORMOUS LENGTH OF GEOLOGICAL ERAS

In order to gain a clear concept of the different lengths of time covered by geological eras, a simple comparison is most helpful. Imagine a comparison between 2,000 million years of the Earth's history with the 24 hours of the day. In such a comparison, the most ancient of the geological eras will take up most of the day and the most recent only the last few seconds.

Imagine starting a day at midnight with a chronometer in hand. The Archeozoic era lasts for 18 hours, or from midnight until 6:00 P.M. This leaves but six hours of time for the four remaining eras. The Paleozoic era lasts for 300 million years, or three hours and thirty-six minutes on this imaginary scale. The Mesozoic era, the period of the dinosaurs, starts at 9:36 p.m. and lasts until 11:10 p.m. The Cenozoic era takes up the rest of the day's time minus 43 seconds. These last 43 seconds, therefore, are the length of the Quaternary era.

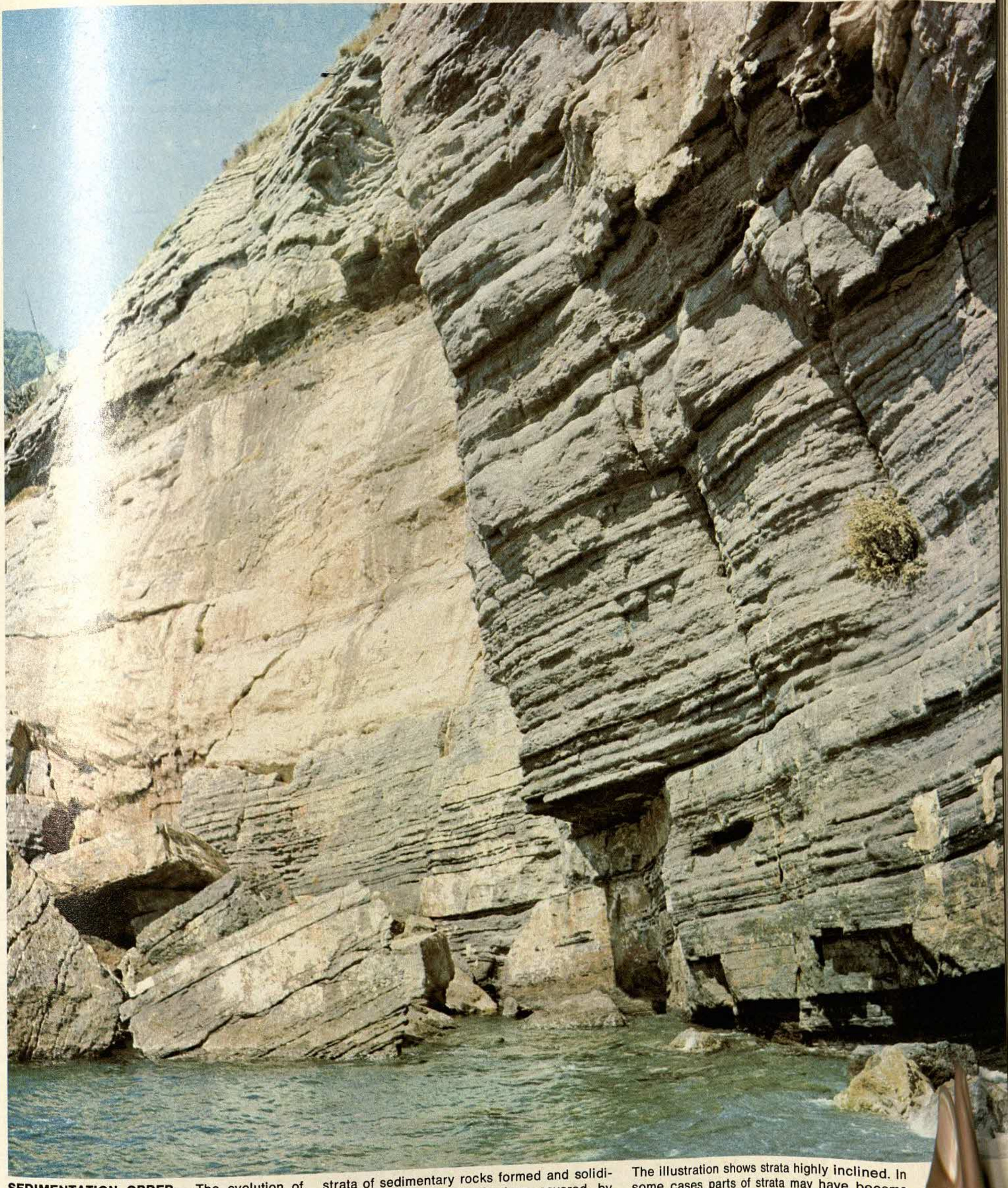
In these 43 seconds four ice ages take place, eroding the Alps and most of the North American and Eurasian continents. These are the same 43 seconds in which man exists. Primitive man learns how to use fire just 20 seconds before midnight. Worship of the dead and the beginning of artistic activity are acquired in the last four seconds. Agriculture and the use of bronze are born at 6 tenths of a second to midnight. How young, then, has been the Iron Age.

ISOTOPIC DATING

Although it is a magnificent achievement to know in which period mammals first appeared and in which period orogeny began in the Alpine Belt, nevertheless relative dating does not indicate how long ago in years the events took place. Provided that suitable materials can be found in critical places, there are ways to find out. Radioactive elements, notably uranium and thorium, emit helium gas at a uniform rate; the end product of the disintegration is an isotope of lead. When a uranium mineral taken from fresh granite is analyzed, the ratio between the uranium and its lead isotope gives the length of time since the granite crystallized. The element lead is involved in a number of methods of age determination. (For a detailed treatment of the method based on the relative uranium and lead content of rock, see THE DATING OF ROCKS, page 1[illegible].)

Another means of dating uses the elements potassium and argon. Preferred for dating the older Precambrian rocks is still another method, based on strontium-rubidium ratios. Certain modifications in the scale of time have been made since a growing number of isotopic dates have been set; and authorities and classification methods differ.

Rates of radioactive disintegration are exceedingly slow, and the dating methods based on them are unsuitable for determining dates late in the Cenozoic era. For late events on the geological time scale, a dating technique was developed that makes use of the carbon isotope ^{14}C, or radiocarbon. The activity of this isotope declines at a known rate. Small amounts of radiocarbon are present in the carbon dioxide of the atmosphere. They are present in the growing tissues of plants and animals. Such durable tissues as wood retain measurable quantities long after the organism has died. With the radiocarbon method of dating, analyses of selected materials give reliable dates for a range of more than 40 thousand years. This range encompasses late stages of the ice sheets and some of the activities of prehistoric man.



SEDIMENTATION ORDER — The evolution of the Earth's crust is studied by analyzing the succession of events that led to the formation of rocks and sediments. The simplest criterion is that of the order of overlying layers: strata of sedimentary rocks formed and solidified atop older strata, in turn covered by younger strata. This method is not always accurate, however, because movements within the Earth's crust can warp and fold rock strata. The illustration shows strata highly inclined. In some cases parts of strata may have become vertical. Such strata must be observed along their entire horizontal extension to determine which are older and which are younger.

GEOLOGICAL CLOCKS | radioactive dating methods

POTASSIUM IN FELDSPAR — Much of the argon in the Earth's atmosphere has probably been produced by radioactive decay of potassium in igneous rocks containing potassium feldspar. Often the argon is trapped between atoms in the crystals. However, by extracting the argon and measuring with a mass spectrograph the ratio between the atoms of argon and those of potassium, the age of the sample can be determined.

The latest methods of geologic age dating are based on radioactivity—its parent-daughter isotope relationships and its effect on its surroundings. These methods are the results of increased knowledge of radioactivity through advances in mass spectrometry and in solid state physics.

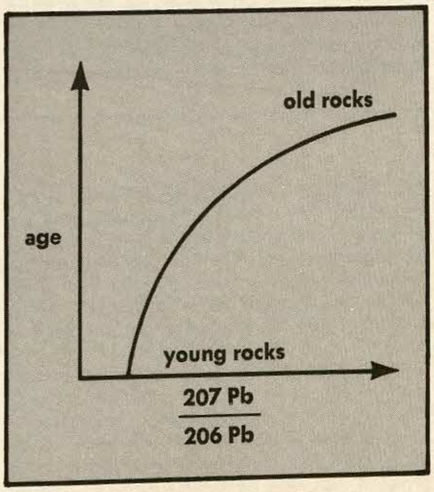
The methods used for dating older rocks, from millions to hundreds of millions of years old, are the uranium-lead method (called the uranium-235/uranium-238, or lead-207/lead-206 method), the potassium-argon method, the rubidium-strontium method, and a method based on changes in the crystal lattice of the mineral zircon. These methods have been used to date the oldest rocks on earth, meteorites and most recently moon rocks. Such methods lose their accuracy if the minerals formed during radioactive decay have become soluble, or if the rocks themselves are heated.

The potassium-argon method depends on the conversion of potassium-40, with a half-life of 1.3 billion years, into argon-40. Potassium is widely distributed in common rocks, such as the glauconite and sylvite of sedimentary rocks and the micas, feldspars, and hornblendes of metamorphic and igneous rocks. Consequently, this has become the most generally used method, although it cannot be used for dating rocks more than 100 million years old. Both the potassium-argon method and the rubidium-strontium method, which is preferred for dating Precambrian rock, are being improved with better analytical techniques. The decay constants that have been difficult to determine—except indirectly by comparison with each other and the lead method—are also gaining precision.

The age of younger rocks—those tens of thousands of years old or less—is determined by the carbon-14 method. Carbon-14 dating is a rate clock in that the actual decay rate of carbon-14 is measured as opposed to the quantity of the daughter species as in the methods above.

2a

2b



2c

THE LEAD-207/LEAD-206 METHOD — This method is based on the isotopic ratio between uranium-238 and uranium-235, in which the first is transformed into lead-206, and the latter into lead-207. This ratio changes continually from the moment the rock solidifies, so that the age of the sample can be determined. Sample rock (Illustration 2c) is ground to produce a fine powder. Then either the powder itself or fragments of uranium crystal contained in it (Illustration 2a) are analyzed. In the latter case, the fragments are isolated under a microscope. The magma from which the sample comes originally contained both uranium-235 and uranium-238. In 700 million years or more of decay, the number of uranium-235 atoms has been reduced by half. Uranium-238, decaying more slowly, has been reduced to half its original number of atoms in about 4.5 billion years. In earth samples there is only 0.7 percent as much uranium-235 as uranium-238. Uranium-238 generates atoms of lead-206 twenty times slower than uranium-235 generates lead-207. This ratio varies slowly in the course of time.

Illustration 2b shows how the age of a sample may be determined by reading the ratio between the number of atoms of lead-207 and lead-206. If a sample has been partly dissolved in water, the calculations are not affected because the two isotopes dissolve in the same proportion, so that the ratio between them remains constant.

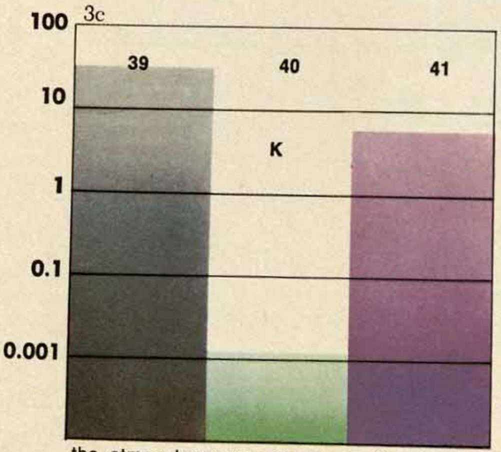
A mass spectrograph is generally used for measurement of lead isotopes.

THE POTASSIUM-ARGON METHOD—The limited utility of the method based on the isotopic ratio of lead, and the general principle of using radioactive substances contained in the minerals of rocks, has led to the search for new methods that can utilize a major constituent of rock rather than a rare component. Such a method is the potassium-argon method.

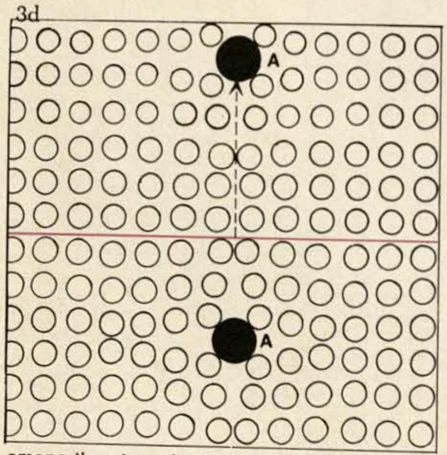
3a

3b

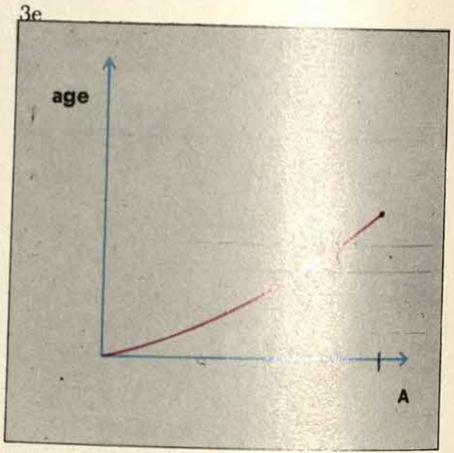
3c



3d



3e

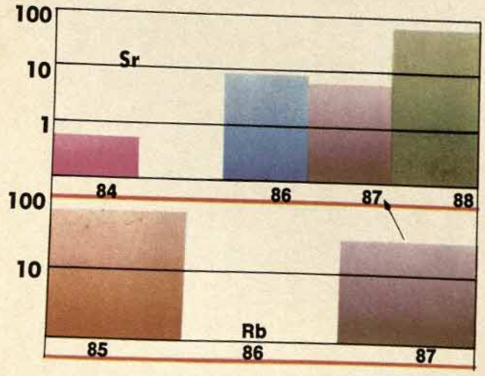


Most effusive and extrusive rocks contain micas (Illustration 3b) and feldspathic minerals (Illustration 3a) that contain a great number of potassium ions. Potassium is composed of three isotopes in the relative proportions shown in Illustration 3c. One of these isotopes is radioactive, and is present in the ratio of one in ten thousand, or slightly more. Its half-life is 1.4 billion years. The mass number of potassium is 40. When decayed, it is transformed into the most common isotope of argon—argon-40. The abundance of this isotope in the atmosphere may be due to the decay of the corresponding isotope of potassium in rocks.

A sample of rock containing mica or feldspar, both rich in potassium, will produce a large quantity of argon gas. The rather large atoms of this gas have difficulty moving among the atoms in the reticular cluster of the mineral, and are sometimes trapped, as shown in Illustration 3d. By measuring with a mass spectrograph the volume of gas freed, and calculating the ratio between it and the amount of potassium that generated the gas, the age of the sample may be determined from a graph such as that of Illustration 3e.

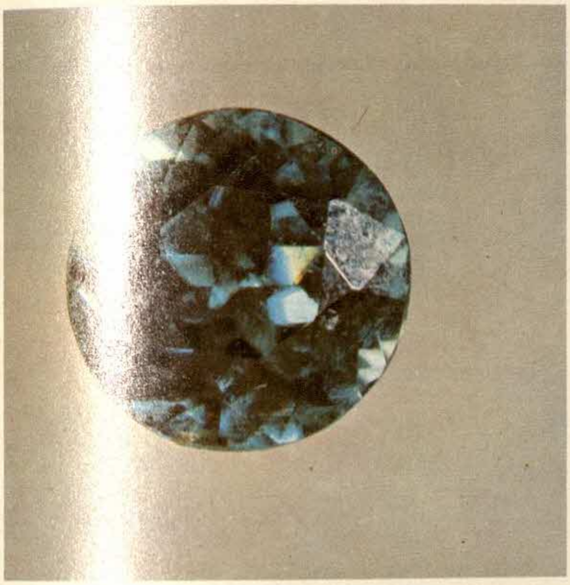
The potassium-argon method is particularly useful in determining the ages of a vast range of igneous and metamorphic rocks. However, it cannot be used to date rocks older than 100 million years because of the slow escape of argon from the crystal lattice.

4

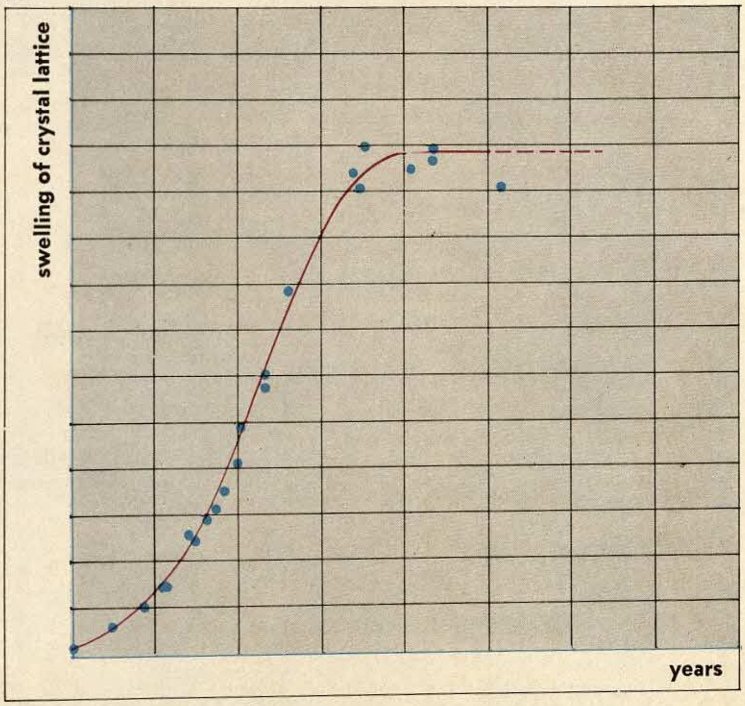


THE RUBIDIUM-STRONTIUM METHOD — Approximately 28 percent of the element rubidium is made up of a radioactive isotope, rubidium-87, which has a half-life of 60 billion years. As it decays, rubidium gives off beta radiations and is transformed into strontium-87, which comprises about 7 percent of the strontium in nature. To calculate the age of a rock, the ratio between the quantity of rubidium and radiogenetic strontium is measured in much the same manner as that used in the uranium-lead method. Both methods are likely to diminish the age of the sample if part of the material has been dissolved in water. Nevertheless, the rubidium-strontium method has proved to be fairly successful.

5a



5c



THE ZIRCON METHOD—Softer than a diamond, zircon (zirconium silicate, ZrCiO$_4$) resembles that stone in its brilliant, transparent appearance and in its ability to break up white light. Rarely is zircon uncovered in pieces as large as that shown in Illustration 5a; it is most commonly found in small pieces in igneous rocks. The purity of its appearance is also deceptive, for zircon contains uranium and thorium, and is often radioactive. Both uranium and thorium give off alpha particles that become stable isotopes of lead.

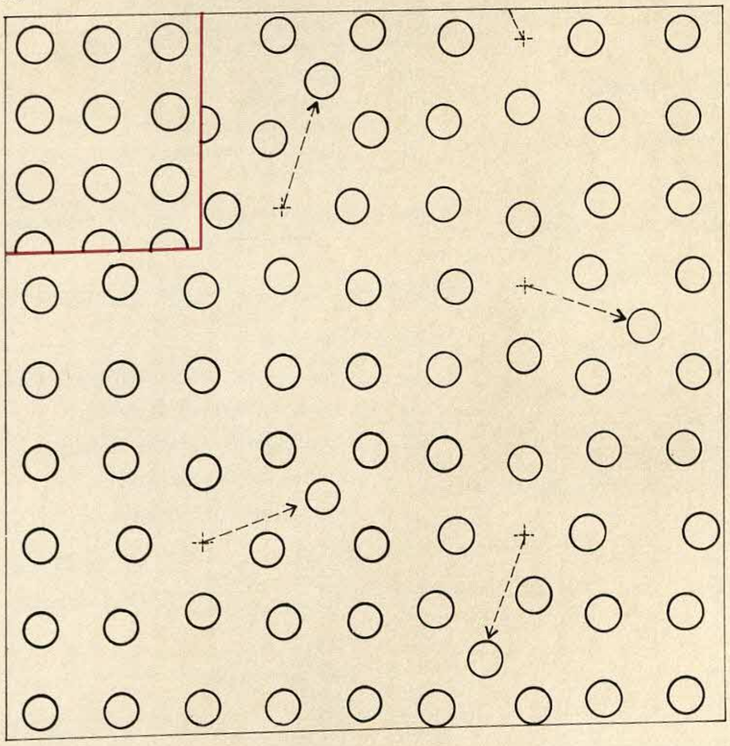
The alpha particles given off by the radioactive substances in zircon displace the atoms as the particles move through and damage the crystal. Illustration 5b shows the displaced atoms and the effect of this displacement on the crystal: the crystal is broken up into smaller crystals of random arrangement and the crystal lattice, which has been forced to make room for the displaced atoms, is swollen.

A graph such as that of Illustration 5c can be used to calculate the new dimensions of the crystal by x-ray, and the average distance between the atoms that compose the crystal. In order to more clearly show the arrangement of the displaced atoms and the changed distance between them, a simpler crystal lattice than that of zircon has been used.

Once the distance between the atoms in that part of the crystal lattice not actually damaged by swelling is known, the amount of swelling is used to calculate the length of time required to damage the crystal by radioactivity. This time is the age of the crystal and of the rock containing it.

The zircon method may cause rocks to appear younger than they are. For example, if a crystal swollen and damaged by radioactivity is then subjected to heat—even a few hundred degrees—most of the displaced atoms return to their original positions and the crystal appears newly formed.

5b



ABBREVIATIONS

A	ampere
Å	Ångstrom unit
abs	absolute
a-c	alternating current (as an adjective)
amu	atomic mass unit
atm	atmosphere
at. wt	atomic weight
AU	astronomical unit
avdp	avoirdupois
Bev	one billion electron volts
bhp	brake horsepower
bhp-hr	brake horsepower-hour
bp	boiling point
Btu	British thermal unit
C	temperature Celsius; temperature Centigrade
c	candle
cal	calorie
cfm	cubic feet per minute
cfs	cubic feet per second
cgs	centimeter-gram-second (system)
cl	centiliter
cm	centimeter
cm^2	square centimeter
cm^3	cubic centimeter
coef	coefficient
colog	cologarithm
cos	cosine
cot	cotangent
cp	candlepower
csc	cosecant
cu	cubic
cu ft	cubic foot
db	decibel
d-c	direct current (as an adjective)
doz	dozen
E	electromotive force
e	the base of the system of natural logarithms
ev	electron volt
F	temperature Fahrenheit
fp	freezing point
fpm	feet per minute
fps	feet per second
ft	foot; feet
ft^2	square foot
ft^3	cubic foot

ft-c	footcandle
ft-lb	foot-pound
G	universal gravitational constant
g	gram
gal	gallon
g-cal	gram-calorie
gpm	gallons per minute
gps	gallons per second
hr	hour
$h\nu$	photon energy
hp	horsepower
Hz	hertz (cycles per second)
I	electric current
ID	inside diameter
in.	inch
$in.^2$	square inch
$in.^3$	cubic inch
in.-lb	inch-pound
ips	inches per second
j	joule
K	temperature Kelvin (absolute)
kcal	kilocalorie
kg	kilogram
kg-cal	kilogram-calorie
kg-m	kilogram-meter
kg/m^3	kilograms per cubic meter
kgps	kilograms per second
km	kilometer
kv	kilovolt
kw	kilowatt
kwhr	kilowatt-hour
l	liter; lumen
lat	latitude
lb	pound
lb-ft	pound-foot
lb/ft^2	pounds per square foot
lb/ft^3	pounds per cubic foot
lb-in.	pound-inch
l-hr	lumen-hour
lin ft	linear foot
log	logarithm (common)
$\log_e$	logarithm (natural)
long.	longitude
m	meter; minute (time, in astronomical circles)

m^2	square meter
m^3	cubic meter
ma	milliampere
Mev	one million electron volts
mg	milligram
mh	millihenry
mi	mile
mi^2	square mile
min	minute
m-kg	meter-kilogram
ml	milliliter
mm	millimeter
mm^2	square millimeter
mm^3	cubic millimeter
mμ	millimicron
mph	miles per hour
mphps	miles per hour per second
mv	millivolt
N	Avogadro's constant
$n!$	factorial n
OD	outside diameter
oz	ounce
pH	rating on acid-alkaline scale
ppm	parts per million
psi	pounds per square inch
psia	pounds per square inch absolute
R	temperature Reaumur; resistance
RA	right ascension
rpm	revolutions per minute
rps	revolutions per second
sec	secant; second
sin	sine
sp gr	specific gravity
sq	square
tan	tangent
V	volt
VA	volt-ampere
W	watt; work
yd	yard
yd^2	square yard
yd^3	cubic yard

SCIENTIFIC SYMBOLS AND ABBREVIATIONS

α	alpha particle
β; β^-	beta particle
β^+	positron
γ	gamma radiation
Δ	a small change; heat
λ	wavelength; radioactive-decay constant
ma	milliampere
μc	microcurie
μf	microfarad
μin.	microinch
μm	micron
μμ	micromicron
μμf	micromicrofarad
ν	frequency; neutrino
π	3.14159; osmotic pressure

Σ	the sum of
σ	nuclear cross section (barns); area
Ω	electrical resistance (ohms)
ω	angular speed; angular velocity
′	minute (angular measure)
″	second (angular measure)
♂	male
♀	female
$>$	is greater than
$<$	is less than
$\propto$	is proportional to
∞	infinity
$\sqrt{}$	square root of
°	degrees; temperature; angle measurement (example, 30°)

[ ]	molar concentration
+	positive electric charge; mixed with; plus
−	negative electric charge; single covalent bond; minus
=	equals; double covalent bond; produces
≠	does not equal
≡	triple covalent bond
→	produces; forms; chemical reaction
⇄	reversible chemical reaction
↑	gas produced by a chemical reaction
↓	precipitate produced by a chemical reaction
•	radioactive substance (follows symbol of element; example, Cl$^\bullet$)

THE
ILLUSTRATED SCIENCE DICTIONARY

Chemical Combination to Conjugate

KEY TO PRONUNCIATION

The diacritical marks are:

ə	b*a*nan*a*, *a*but	e	b*e*t	th	*th*in
ᵊ	preceding l, m, n as in batt*le*	ē	b*ea*t	t̲h̲	*th*en
ə̇	*e*lectric	i	t*i*p	ü	r*u*le, f*oo*l
ər	f*ur*ther	ī	b*i*te	u̇	p*u*ll, w*oo*d
a	m*a*t	j	*j*ob, gem	ue	German h*ü*bsch
ā	d*ay*	ŋ	si*ng*	u̅e̅	French r*ue*
ä	c*o*t, f*a*ther	ō	b*o*ne	yü	*u*nion
au̇	n*ow*, *ou*t	ȯ	s*aw*, *a*ll	zh	vi*si*on
		ȯi	c*oi*n		

ˈ mark preceding the syllable with strongest stress.
ˌ mark preceding a syllable with secondary stress.

The system of indicating pronunciation in these volumes is used by permission from Webster's *Third New International Dictionary*, copyright 1961 by G. & C. Merriam Co., Publishers of the Merriam-Webster Dictionaries.

chemical combination \'kem-i-kəl ˌkäm-bə-'nā-shən\
CHEMISTRY. A simple chemical reaction in which elements combine to form compounds.

The CHEMICAL COMBINATION *of iron and sulfur produces iron sulfide.*

chemical element \'kem-i-kəl 'el-ə-mənt\
CHEMISTRY. An element. See *element.*

chemical energy \'kem-i-kəl 'en-ər-jē\
CHEMISTRY. The energy produced or absorbed in a chemical reaction.

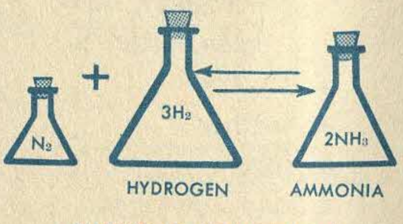
The CHEMICAL ENERGY *in wood, coal and oil is transformed primarily into heat energy when these substances are burned.*

chemical engineering \'kem-i-kəl ˌen-jə-'ni(ə)r-iŋ\
CHEMISTRY and ENGINEERING. A branch of engineering that uses chemical facts and principles for industrial purposes.

Students of CHEMICAL ENGINEERING *study such subjects as flow of heat, crystallization, catalysis, chemical equilibria and mathematics.*

chemical equation \'kem-i-kəl i-'kwā-zhən\
CHEMISTRY. A statement that uses symbols for elements and compounds to indicate the amounts and kinds of changes occurring during a chemical reaction.

The CHEMICAL EQUATION *for the production of sulfur dioxide and energy is* $S+O_2=SO_2+$ *energy.*



CHEMICAL EQUILIBRIUM

chemical equilibrium \'kem-i-kəl ˌē-kwə-'lib-rē-əm\
CHEMISTRY. A balance created and maintained in a chemical reaction when the rate of reaction in one direction equals the rate of reaction in the other direction, assuming that the concentration of the reacting substances remains constant.

CHEMICAL EQUILIBRIUM *in the fluids of the human body is essential to good health.*

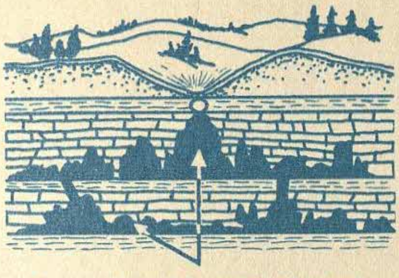
chemical formula \'kem-i-kəl 'fȯr-myə-lə\
CHEMISTRY. A group of symbols for elements that show the combination of atoms, both in number and kind, in a given substance.

The CHEMICAL FORMULA *for sodium carbonate is* Na_2Co_3.

chemical property \ˈkem-i-kəl ˈpräp-ərt-ē\
CHEMISTRY. That quality of a substance that determines whether or how it reacts with other substances.

A CHEMICAL PROPERTY *of hydrogen is its ability to burn and to form water.*

CHEMICAL WEATHERING



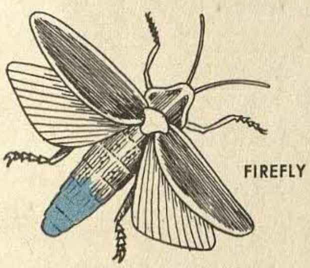
Caverns formed by action of carbon dioxide in water solution on limestone

chemical weathering \ˈkem-i-kəl ˈwet͟h-ər-iŋ\
EARTH SCIENCE. The decomposition of rock materials by chemical processes with a resulting change in the composition and character of the original material.

CHEMICAL WEATHERING *produces clay from feldspar.*

chemiluminescence \ˌkem-ē-ˌlü-mə-ˈnes-ᵊn(t)s\ *n.*
CHEMISTRY and PHYSICS. The direct transformation of chemical energy into light energy for reasons other than the high temperature of the reactants.

The light of a firefly is an example of CHEMILUMINESCENCE.



CHEMILUMINESCENCE

chemist \ˈkem-əst\ *n.*
CHEMISTRY. One who has been educated in one or more of the fields of chemistry, or one who applies chemical principles in a laboratory.

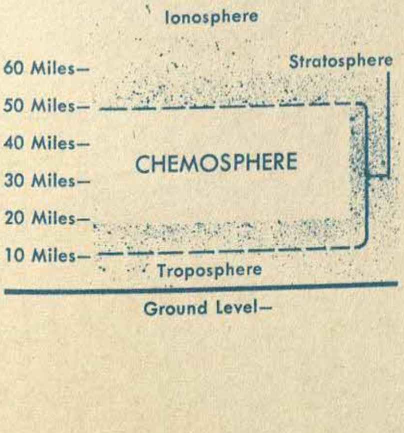
A CHEMIST *may specialize in one of the various fields of chemistry, such as inorganic, organic, analytical, synthetic, radiochemistry, biochemistry, geochemistry or agricultural chemistry.*

chemistry \ˈkem-ə-strē\ *n.*
The science pertaining to matter, its composition and structure, its change in composition and the related changes in energy.

Organic CHEMISTRY *deals with carbon compounds.*

chemosphere \ˈkem-ō-ˌsfi(ə)r\ *n.*
EARTH SCIENCE. A layer of the atmosphere that contains ozone and begins in the upper stratosphere and extends into the ionosphere. The chemosphere is generally regarded as beginning about 15 miles above the earth's surface and is sometimes called the ozone layer.

The CHEMOSPHERE *absorbs ultraviolet rays, resulting in the conversion of oxygen molecules (O_2) to ozone (O_3).*

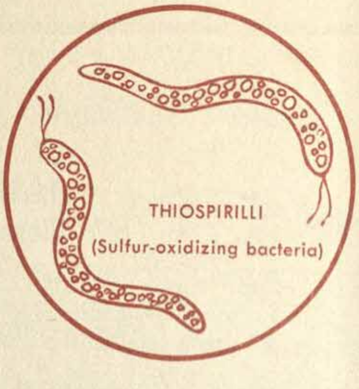


chemosynthesis \ˌkem-ō-ˈsin(t)-thə-səs\ *n.*
BOTANY. In plants, the synthesis of organic compounds by use of the energy released during chemical reactions; contrasted with photosynthesis that uses the energy of light.

Certain bacteria manufacture their food by CHEMOSYNTHESIS.

chemotaxis \ˌkem-ō-ˈtak-səs\ *n.*
BIOLOGY. The movement of cells or organisms away from or toward a chemical stimulus.

The attraction between male and female cells is an example of CHEMOTAXIS.



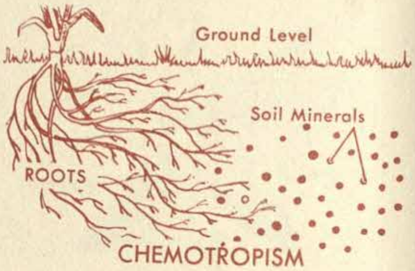
CHEMOTROPH

chemotherapy \ˌkem-ō-ˈther-ə-pē\ *n.*
MEDICINE. The control or destruction of parasites or disease-producing organisms in the body by the use of chemicals that do not harm the body itself.

Malaria can be controlled by CHEMOTHERAPY.

chemotroph \ˈkem-ō-ˌträf\ *n.*
BIOLOGY. A kind of autotroph that gets its food-making energy from inorganic materials in its environment rather than from light.

Some scientists describe the CHEMOTROPH *as a chemosynthetic autotroph.*



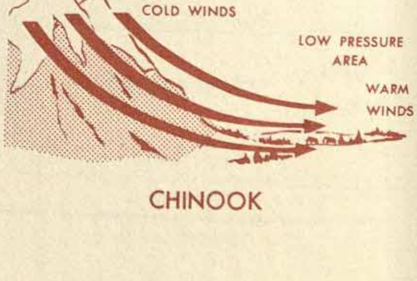
CHEMOTROPISM

chemotropism \ke-ˈmä-trə-ˌpiz-əm\ *n.*
BIOLOGY. The reaction of an organism, or any of its parts, in turning toward or away from a chemical stimulus.

The growth of a root toward a region where a specific chemical substance is in high concentration is CHEMOTROPISM.

chert \ˈchərt\ *n.*
EARTH SCIENCE. An extremely fine-grained variety of silica (quartz) frequently present as nodules in limestone formations.

Flint is a variety of CHERT *that is usually brown, gray or black.*



CHINOOK

chinook \shə-ˈnük\ *n.*
EARTH SCIENCE. A type of southwest wind characteristic of the Sierra Nevada and Rocky Mountain regions. A chinook moves rapidly down the eastern sides of mountains toward a low-pressure area, the air temperature increasing about 5.5° F. for each 1,000 feet it descends. It is most common in winter and spring when the wind melts snow and creates warm temperatures in the valleys to the east.

A CHINOOK *may raise the atmospheric temperature 30° or more in a 15-minute period.*

chi-square \\'kī-'skwa(ə)r\\ *n.*

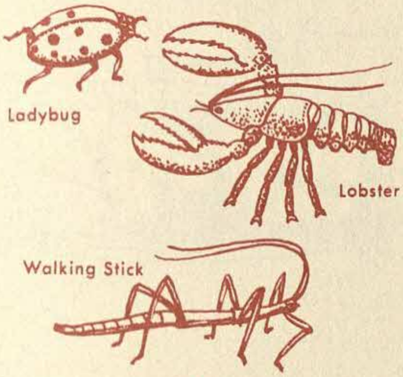
MATHEMATICS. In statistics, a formula used to test the deviation between one or more observed frequencies and a theoretical frequency.

Scientists sometimes apply CHI-SQUARE *to biological data.*

chitin \\'kīt-ᵊn\\ *n.*

ZOOLOGY. A hard, waterproof, inelastic secretion forming the exoskeleton of such arthropods as the lobster.

Since CHITIN *is inelastic, growing animals that have chitinous exoskeletons must shed them at intervals.*



CHITIN
(EXOSKELETONS)

chlorate \\'klō(ə)r-ˌāt\\ *n.*

CHEMISTRY. A salt of chloric acid ($HClO_3$), soluble in water, such as sodium chlorate ($NaClO_3$).

If a small amount of manganese dioxide, MnO_2, is mixed with potassium chlorate, $KClO_3$, and the mixture is heated, oxygen is released from the CHLORATE.

chloride \\'klō(ə)r-ˌīd\\ *n.*

CHEMISTRY. A compound of chlorine and another element or radical.

Common table salt is sodium CHLORIDE.

chlorinate \\'klōr-ə-ˌnāt\\ *v.*

CHEMISTRY. To react with chlorine; also, to add chlorine to, or to substitute chlorine in, a compound; in general use, to purify by oxidation with chlorine.

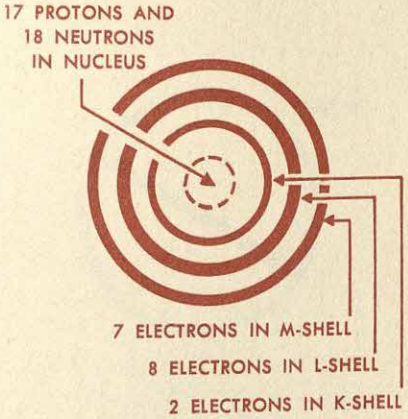
It is necessary to CHLORINATE *the water in a swimming pool to destroy bacteria.*

chlorine \\'klō(ə)r-ˌēn\\ *n.*

CHEMISTRY and EARTH SCIENCE. A gaseous element having a light green-yellow color and a suffocating odor. It occurs in nature in combination with metallic elements. Symbol, Cl; atomic number, 17; atomic weight, 35.453.

Large quantities of CHLORINE *are prepared by the electrolysis of melted sodium chloride.*

CHLORINE (ATOM)



chlorite \\'klō(ə)r-ˌīt\\ *n.*

1. CHEMISTRY. A salt of chlorous acid ($HClO_2$); the anion ClO_2^-. 2. EARTH SCIENCE. A soft, green mineral having vitreous to pearly luster, a micalike cleavage and composed of hydrous magnesium aluminum silicate.

The formula for potassium CHLORITE *is $KClO_2$.*

chlorophyll \'klōr-ə-ˌfil\ *n.*

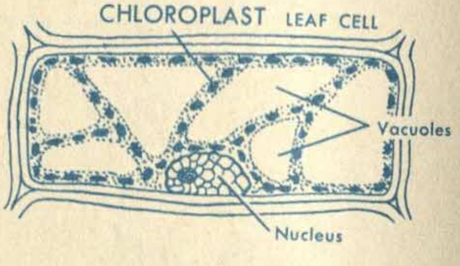
BOTANY. The green coloring matter present in most plants and essential to the process of photosynthesis. Of the different kinds, *chlorophyll a* and *chlorophyll b* are the characteristic chlorophylls of higher plants.

Except for blue-green algae and photosynthetic bacteria, CHLOROPHYLL *is found in the chloroplasts in plant cells.*

chloroplast \'klōr-ə-ˌplast\ *n.*

BOTANY. A chlorophyll-containing body, or plastid, found in the cytoplasm of many plant cells.

Photosynthesis occurs in the CHLOROPLAST.



choke coil \'chōk 'kȯil\

ENGINEERING and PHYSICS. A coil used in an electric circuit to impede or reduce certain frequencies, particularly high frequencies; an induction coil.

A CHOKE COIL *with an air core may be used in an electric power circuit to reduce the momentary surges of current produced by lightning.*

cholesterol \kə-'les-tə-ˌrōl\ *n.*

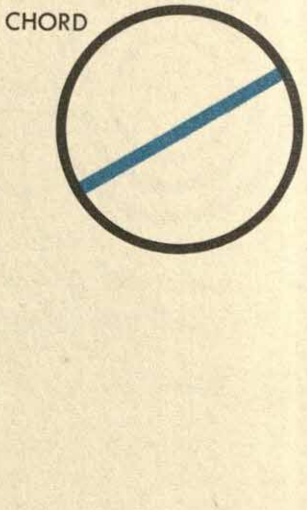
BIOLOGY and CHEMISTRY. $C_{27}H_{45}OH$. A heavy, white or colorless alcohol having no characteristic taste or odor and found primarily in animal tissues.

Since CHOLESTEROL *is only slightly soluble, it may form the nucleus of a gallstone in the gall bladder.*

chord \'kȯ(ə)rd\ *n.*

1. MATHEMATICS. In geometry, any straight line connecting any two points on a curve. 2. AERONAUTICS. A straight line joining the leading and trailing edges of an airfoil profile. 3. PHYSICS. In music, a harmonious combination of tones sounded together, the ratios of their pitch frequencies being small whole numbers.

The diameter of a circle is a CHORD *that passes through the center of the circle.*



Chordata \kȯr-'dät-ə\ *n.*

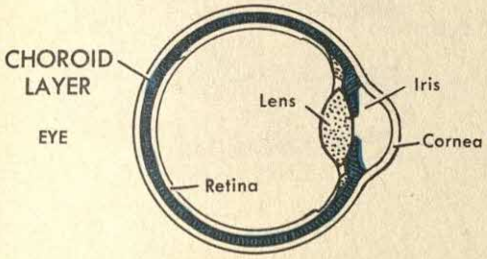
ZOOLOGY. The phylum of vertebrates, and a few marine animals of simpler form, that have an internal skeleton and, at some stage in their development, a notochord (an internal supporting rod over the length of the body) and gill slits (respiratory openings) or pouches.

The phylum CHORDATA *includes the subphylum Vertebrata, that in turn includes five classes commonly referred to as fish, birds, amphibians, reptiles and mammals.*

choroid layer \'kōr-ˌȯid 'lā-ər\

ANATOMY and ZOOLOGY. The dark second, or inside, layer of the eyeball of vertebrates. The layer contains blood vessels and color cells and lies between the sclera and the retina.

The function of the CHOROID LAYER *is to nourish the retina and lens and to darken the inside of the eye.*



chromatic \krō-'mat-ik\ *adj.*

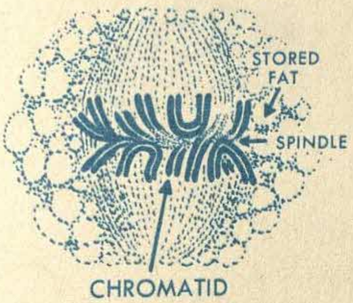
PHYSICS. Relating to or having color; also, referring to the musical scale made up of 13 tones to the octave and consisting of the 8 notes of the diatonic scale and the 5 intermediate semitones.

CHROMATIC *sensitivity in the eye enables it to distinguish colors.*

chromatic aberration \krō-'mat-ik ˌab-ə-'rā-shən\

PHYSICS. The failure of a lens to bring the different colors in light to a single focus, resulting in color effects along the edges of the images of objects. Chromatic aberration is caused by unequal refraction of colors passing through the lens.

CHROMATIC ABERRATION *in a single lens can be partially eliminated by the substitution of a two-part lens system, one lens made of crown glass and the other of flint glass.*



chromatid \'krō-mə-təd\ *n.*

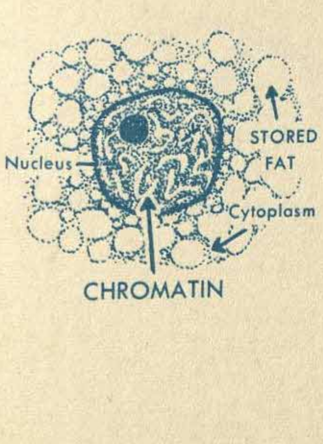
BIOLOGY. One of two parallel strands formed by longitudinal splitting of a chromosome in somatic mitosis; also, one of four strands formed from paired chromosomes during a phase of meiosis.

A better understanding of the structure of the CHROMATID *is necessary to more adequately explain heredity.*

chromatin \'krō-mə-tən\ *n.*

BIOLOGY. The granular materials occurring in the nucleus of a cell and forming the most conspicuous part of the nuclear network and the chromosomes.

CHROMATIN *is regarded as the carrier of the hereditary characteristics of an organism.*



chromatography \ˌkrō-mə-'täg-rə-fē\ *n.*

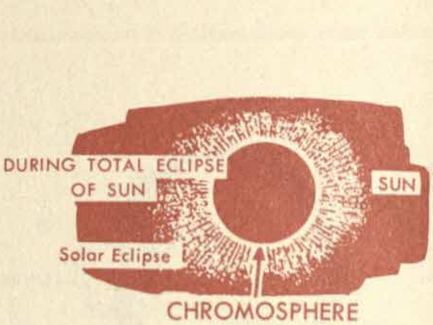
CHEMISTRY. A process by which certain components of a mixture can be separated by their different rates of travel in an adsorbing medium. This process is used to separate ions of elements with similar properties.

The molecules of the two types of chlorophyll can be separated and identified by CHROMATOGRAPHY.

chromite \\'krō-ˌmīt\\ *n.*

EARTH SCIENCE. $FeCr_2O_4$. A black or dark-brown mineral with submetallic luster, generally found in igneous rocks as a granular mass; the principal chromium ore.

Bricks containing CHROMITE *are used to line metallurgical furnaces, because the chromite withstands high temperatures.*



CHROMOSPHERE

chromosome \\'krō-mə-ˌsōm\\ *n.*

BIOLOGY. Any of the microscopic, threadlike, hereditary bodies developing from chromatin in a cell nucleus prior to cell division and occurring in constant number, size and form for each species.

In some insects, the female has one more CHROMOSOME *than the male.*

chromosphere \\'krō-mə-ˌsfi(ə)r\\ *n.*

ASTRONOMY. The reddish layer of luminous gas in the sun's atmosphere, from which flamelike jets of hydrogen and other gases are ejected; in general, the shell of gas around a star.

The CHROMOSPHERE *is visible to the naked eye only during an eclipse of the sun.*

CHRONOMETER

chronology \\krə-'näl-ə-jē\\ *n.*

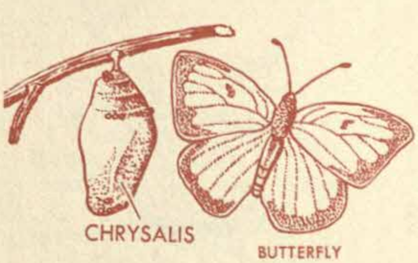
1. EARTH SCIENCE. The science of arranging earth history in definite time divisions. 2. Any listing of events in their successive order; also, the dating of events.

The CHRONOLOGY *of the earth's natural history covers millions of years and is represented by the geologic time table.*

chronometer \\krə-'näm-ət-ər\\ *n.*

An extremely accurate clock or timepiece; also, a type of sundial, some of which give the month, day and time of day for any place on the earth.

A navigator uses a CHRONOMETER *to determine the exact time when a change in course is made.*



CHRYSALIS

BUTTERFLY

chrysalis \\'kris-ə-ləs\\ *n.*

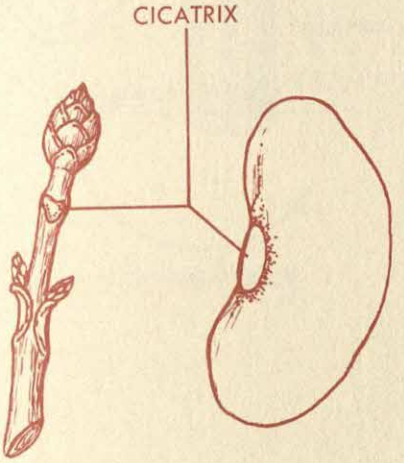
ZOOLOGY. An undeveloped butterfly, called a pupa, in a protective covering.

Although some moths form pupae similar to those of butterflies, the term CHRYSALIS *is applied only to the pupae of butterflies.*

chyle \'kī(ə)l\ *n.*

PHYSIOLOGY. The milky fluid in the intestines that is taken from digested food.

CHYLE *is made up of lymph and emulsified fats.*



chyme \'kīm\ *n.*

PHYSIOLOGY. The semiliquid, pulpy mass of partially-digested food that moves from the stomach into the small intestine.

Chyle is formed from CHYME *as digestion continues in the small intestine.*

cicatrix \'sik-ə-ˌtriks\ *n.*

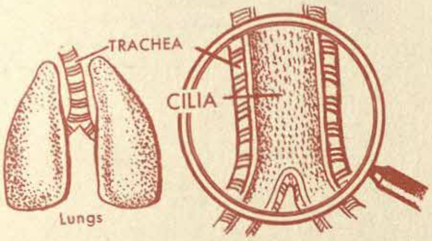
1. PHYSIOLOGY. The fibrous tissue found where a wound has healed; a scar. 2. BOTANY. The scar left on a stem where a leaf or twig was formerly attached; also, the scar left on a tree where a branch has broken or been removed; also, the scarlike mark (hilum) on a seed where it was once fastened to the pod.

The CICATRIX *from a deep wound will remain as a permanent marking.*

cilia \'sil-ē-ə\ *n.*

ANATOMY and ZOOLOGY. Tiny hairlike structures attached to the free surface of a cell and capable of vibratory motion.

Many cells of the upper respiratory tract possess CILIA *that sweep out foreign matter inhaled with air.*



cinder cone \'sin-dər 'kōn\

EARTH SCIENCE. A cone-shaped accumulation of volcanic ash around the vent of a volcano.

A CINDER CONE *may build up to 1,500 feet in height and have a slope of 30 to 40 degrees.*

cinnabar \'sin-ə-ˌbär\ *n.*

EARTH SCIENCE. HgS. A bright red mineral, mercuric sulfide, that is the chief source of mercury.

Mercury obtained from CINNABAR *is used in thermometers, barometers, special batteries, drugs and dental fillings and in silvering mirrors.*

circle \'sər-kəl\ *n.*

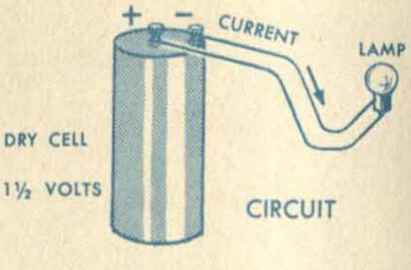
MATHEMATICS. A closed curve on which all points are the same distance from a given point called the center.

The CIRCLE *is the most common conic section used in elementary and high-school mathematics.*

circuit \'sər-kət\ *n.*

ENGINEERING and PHYSICS. A complete route through which electricity passes, including a source, such as a cell or generator, a conductor and such devices as bulbs, meters, switches and fuses.

Diagrams can be drawn to represent an electric CIRCUIT.



CIRCUIT

circuit breaker \'sər-kət 'brā-kər\

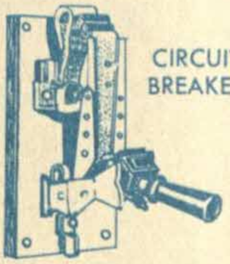
ENGINEERING. A mechanism, generally automatic, acting as a switch to break, or interrupt, a circuit when the current load becomes too large.

A CIRCUIT BREAKER *acts as a protective measure against fire.*

circular measure \'sər-kyə-lər 'mezh-ər\

MATHEMATICS. A system for measuring an arc of a circle by applying some standard proportionate unit, such as degree, minute, second or radian. It is also used in measuring angles.

The CIRCULAR MEASURE *for the quadrant of a circle is 90 degrees.*



CIRCUIT BREAKER

circular mil \'sər-kyə-lər 'mil\

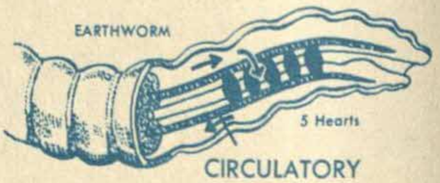
ENGINEERING. A standard unit based on a mil (1/1,000 of an inch) used to measure the cross-sectional area of wires. For example, the area of a circle having a diameter of r mils is r^2 circular mils.

The CIRCULAR MIL *is a more convenient unit of measurement than the square inch because it does not involve the factor* π *(pi).*

circulating decimal \'sər-kyə-ˌlāt-iŋ 'des-ə-məl\

MATHEMATICS. A decimal in which two or more numbers reappear at successive intervals.

An example of a CIRCULATING DECIMAL *is 0.421421421421.*

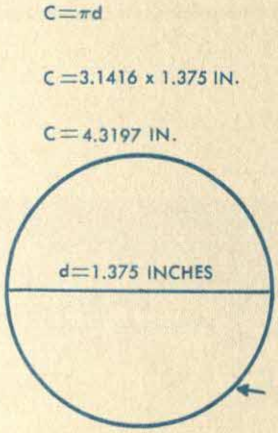


CIRCULATORY SYSTEM

circulatory system \'sər-kyə-lə-ˌtōr-ē 'sis-təm\

ANATOMY and ZOOLOGY. A closed network through which blood and the materials in it are routed to the various parts of the body; also, the network that carries lymph.

Blood in the CIRCULATORY SYSTEM *of man moves from the heart through arteries to arterioles, to capillaries, to venules and back to the heart through veins.*



CIRCUMFERENCE

circumference \sə(r)-ˈkəm(p)-fərn(t)s\ *n.*

MATHEMATICS. The perimeter, or distance, around a closed curve.

The CIRCUMFERENCE *of a circle may be found by multiplying the diameter of the circle by π (pi).*

circumpolar star \ˌsər-kəm-ˈpō-lər ˈstär\

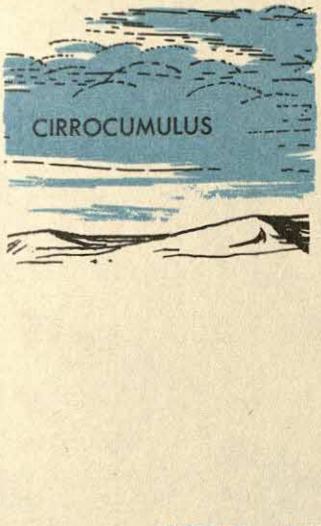
ASTRONOMY. A star that appears never to set because it is closer to either the north or south celestial pole than that pole is to the horizon.

The North Star is a CIRCUMPOLAR STAR *about one degree from the celestial north pole.*

circumscribe \ˈsər-kəm-ˌskrīb\ *v.*

MATHEMATICS. To draw or construct a polygon, or polyhedron, about a closed curve, or curved surface, so that the sides of the polygon, or polyhedron, are tangent to the curve, or curved surface; also, to draw or construct a closed curve about a polygon so that the curve passes through the vertices of the polygon in such a way that the sides of the polygon lie inside the closed curve; also, to draw or construct a curved surface about a polyhedron.

It is always possible to CIRCUMSCRIBE *a sphere about a regular tetrahedron.*



cirque \ˈsərk\ *n.*

EARTH SCIENCE. A steep-sided, bowl-shaped depression formed by glacial erosion on a mountainside.

A lake is often formed in the bowl of a CIRQUE *when the glacial ice melts.*

cirrocumulus \ˌsir-(ˌ)ō-ˈkyü-myə-ləs\ *adj.*

EARTH SCIENCE. Referring to white, fleecelike clouds that occur at an altitude of about 20,000 feet, have a rippled or grainy appearance and usually indicate a change in weather.

Regular groupings of CIRROCUMULUS *clouds are often known as a mackerel sky.*

cirrostratus \ˌsir-(ˌ)ō-ˈstrāt-əs\ *adj.*

EARTH SCIENCE. Referring to a faint, hazy cloud formation, creating at times a halo effect around the sun or moon.

The outline of the moon can be seen clearly through a CIRROSTRATUS *cloud.*

cirrus \'sir-əs\

1. EARTH SCIENCE (Adj.). Referring to a fibrous or feathery-appearing cloud that consists of tiny ice crystals and occurs at an altitude of about 20,000 feet. 2. BOTANY (N.). A tendril. 3. ZOOLOGY (N.). A threadlike, flexible growth or appendage, such as a barbel on a fish.

A CIRRUS *cloud is sometimes referred to as a "mare's tail" because of its tufted, feathery form.*

cislunar space \(')sis-'lü-nər 'spās\

ASTRONAUTICS. The space existing between the earth and the orbit of the moon.

A Russian satellite launched January 2, 1959, which went into orbit around the sun, may have been the first man-made object to pass beyond the limits of CISLUNAR SPACE.

citrate \'si-ˌtrāt\ *n.*

CHEMISTRY. A salt or ester of citric acid.

A solution of magnesium CITRATE *is sometimes used as a medicine.*

citric acid \'si-trik 'as-əd\

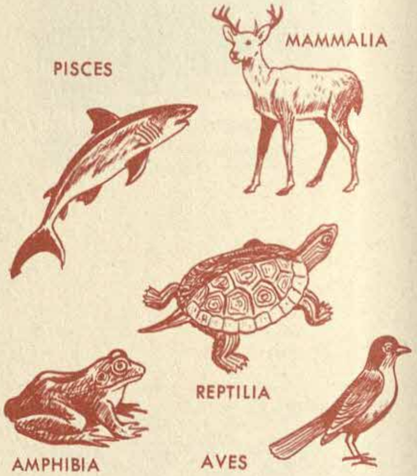
CHEMISTRY. $COOH(OH)C(CH_2COOH)_2$. A white crystalline solid found in the juice of many fruits, such as oranges, grapefruits and lemons.

The CITRIC ACID *used to flavor soft drinks is usually produced synthetically.*

class \'klas\ *n.*

BIOLOGY. One of the divisions of a plant or animal phylum that is subdivided into orders.

A grasshopper belongs to the phylum Arthropoda and the CLASS *Insecta.*



CLASS
(phylum Chordata)

clay \'klā\ *n.*

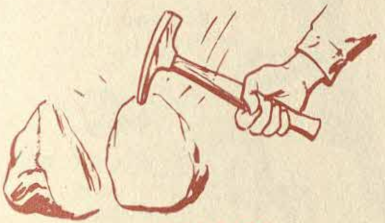
EARTH SCIENCE. Soil with particles less than 1/256 mm. (.00015 inch) in diameter; also, material that has plastic properties when wet; also, a soil composed of clay minerals.

CLAY *is formed as a result of the weathering of preexisting rock.*

clay minerals \'klā 'min-(ə-)rəlz\

EARTH SCIENCE. A group of complex, hydrous silicates with a finely-crystalline structure and a wide range of colors caused by impurities. Clay minerals are formed as a result of the weathering of feldspar, pyroxene or amphibole.

Kaolinite is one of the CLAY MINERALS *used in the production of pottery.*



CLEAVAGE

cleavage \'klē-vij\ *n.*

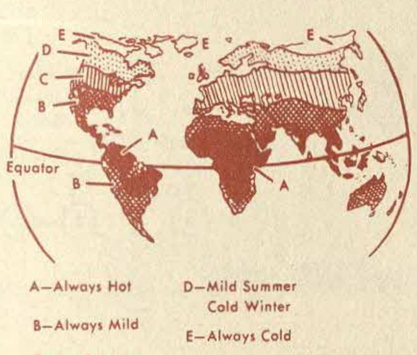
EARTH SCIENCE. The property of certain minerals and rocks that results in a tendency to split along definite, closely-spaced parallel planes.

Mineral CLEAVAGE *is determined by the crystalline pattern in which the atomic structure controls the direction of easiest splitting.*

climate \'klī-mət\ *n.*

EARTH SCIENCE. The characteristic atmospheric condition in a given area, determined by averaging over a long period of time all meteorological quantities, such as temperature, pressure, winds, moisture and evaporation.

The meteorological conditions that determine the CLIMATE *of a region are influenced by its latitude, the local topographic conditions and its relation to land masses and bodies of water.*



CLIMATIC ZONES

climatic biome \klī-'mat-ik 'bī-ˌōm\

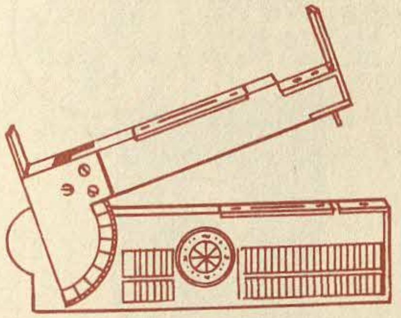
BIOLOGY and EARTH SCIENCE. One of the four major ecological divisions into which the terrestrial portions of the earth are arbitrarily divided by ecologists. The other divisions are edaphic, pioneer and climax biomes.

Polar regions form a CLIMATIC BIOME *that includes such specific divisions as tundra, snow forest and perpetual frost climates.*

climatic zones \klī-'mat-ik 'zōnz\

EARTH SCIENCE. The divisions of the surface of the earth that have a typical climate, such as Torrid, Temperate and Frigid zones.

Differences in animals and plants across the earth are due in part to their adaptation to various CLIMATIC ZONES.



CLINOMETER

climax biome \'klī-ˌmaks 'bī-ˌōm\

BIOLOGY. The final and more or less permanent community of plants and animals in a region, such as a tall-grass prairie or a beech-maple forest.

A CLIMAX BIOME *does not change appreciably unless the climate changes.*

clinometer \klī-'näm-ət-ər\ *n.*

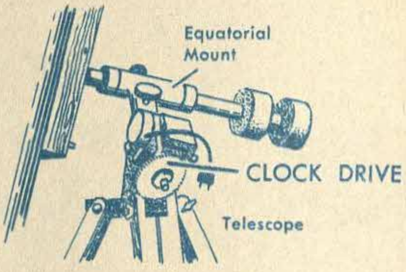
ENGINEERING. An instrument consisting of a level indicator and a circular scale and used to measure vertical angles.

Geologists may use a CLINOMETER *to measure the inclination or dip of a rock stratum.*

cloaca \klō-'ā-kə\ *n.*

ZOOLOGY. In amphibians, birds, reptiles and most fish, the common passageway into which the waste products and reproductive cells are discharged.

Frogs and chickens have a CLOACA.

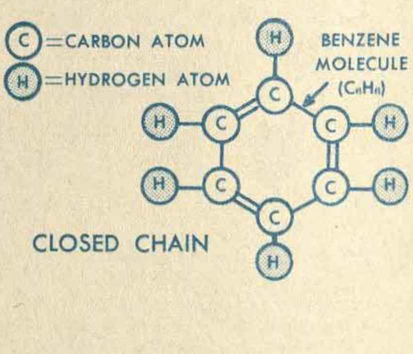


CLOCK DRIVE

clock drive \'kläk 'drīv\

ASTRONOMY. An automatic mechanism designed to rotate a telescope and to keep it pointed toward an object in space, and that, if allowed to operate continuously, will turn the barrel of the telescope in a complete circle every 23 hours and 56 minutes.

The CLOCK DRIVE *on a telescope is a valuable aid when making time-exposure photographs of planets because it maintains the position of the image on the film.*



CLOSED CHAIN

clone \'klōn\ *n.*

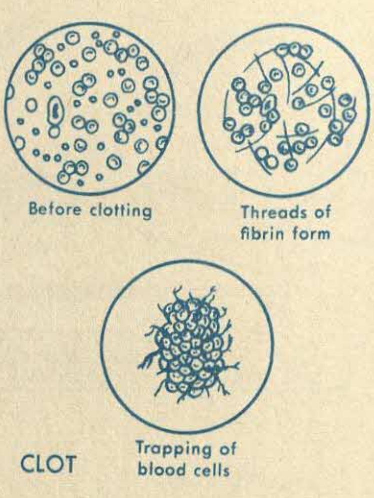
BIOLOGY. A group of animals or plants produced from a single parent by any form of asexual reproduction, such as budding, cell division or grafting.

The members of a CLONE, *since they have a common parent, all have the same hereditary characteristics.*

closed chain \'klōzd chān\

CHEMISTRY. In some chemical elements and compounds, the molecular structure in which the atoms are linked together in the form of a ring; see *chain* (1).

The carbon atoms in a benzene molecule are in the form of a CLOSED CHAIN.



Before clotting

Threads of fibrin form

Trapping of blood cells

CLOT

closed ecological system \'klōzd ˌek-ə-'läj-i-kəl 'sis-təm\

ASTRONAUTICS. In a spacecraft, a system that converts carbon dioxide and other body wastes into oxygen and food. This process is called recycling.

In one proposed CLOSED ECOLOGICAL SYSTEM, *waste products will be converted into oxygen and food by the photosynthetic activity of green plants.*

clot \'klät\ *n.*

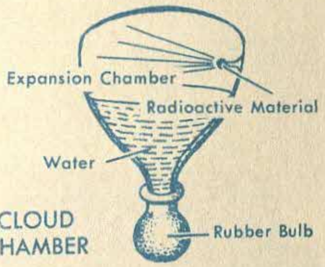
PHYSIOLOGY. A network of fibrous strands in which corpuscles are trapped; a coagulation of the blood or lymph.

The liver must receive vitamin K to produce prothrombin, a substance needed to form a blood CLOT.

cloud \'klau̇d\ *n.*

EARTH SCIENCE. An accumulation of small water droplets or ice crystals formed by condensation of the water vapor in the atmosphere when the air is cooled below its saturation point.

A CLOUD *is classified either as "cumulus," formed by rising air currents, or "stratus," formed when a layer of air is cooled sufficiently to cause condensation.*



CLOUD CHAMBER

cloud chamber \'klau̇d 'chām-bər\

PHYSICS. An enclosed chamber used to detect and measure certain properties of ionizing radiation; a chamber in which the tracks of ionizing radiation can be traced by the condensation of the saturated water vapor on the ionized particles produced.

A CLOUD CHAMBER *can be used to study the properties of the particles produced by nuclear disintegration.*

cloud satellite \'klau̇d 'sat-ᵊl-ˌīt\

ASTRONAUTICS and EARTH SCIENCE. A satellite especially designed to study cloud cover and weather conditions; sometimes called weather satellite, or meteorological satellite.

Any satellite in the Tiros, Nimbus, and Aeros series is a CLOUD SATELLITE.

CLOUD SEEDING

cloud seeding \'klau̇d 'sēd-iŋ\

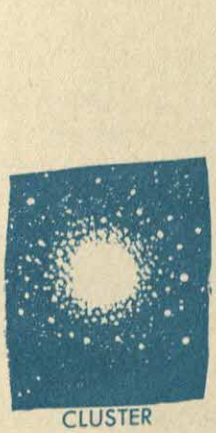
EARTH SCIENCE. Scattering chemicals, such as dry ice or silver iodide, in a cloud that has a potential for producing rain.

CLOUD SEEDING *is most effective when the cloud has nearly the right conditions for natural precipitation.*

cluster \'kləs-tər\ *n.*

1. ASTRONOMY. A grouping of stars whose relative distances from each other are less than the distance of the group from other stars. 2. BOTANY. In plants, a grouping of individual parts having the same structure and maturing together, such as bananas or grapes.

Probably the best-known star CLUSTER *is the Pleiades, or the Seven Sisters, located in the constellation Taurus.*



CLUSTER

cm.

An abbreviation for centimeter. See *centimeter.*

coagulant \kō-'ag-yə-lənt\ *n.*

CHEMISTRY and PHYSIOLOGY. A substance that causes, or tends to cause, a liquid to thicken, clot or congeal.

A COAGULANT *is produced when aluminum sulfate and calcium hydroxide are added to water to help remove any suspended particles, such as those of clay.*

coagulation \(,)kō-,ag-yə-'lā-shən\ *n.*
1. PHYSIOLOGY. The process by which certain blood plasma proteins are changed into a clot. 2. CHEMISTRY. In colloids, the changing of a sol into a gelatinous mass.

COAGULATION *of the blood is usually not reversible.*

coalescence \,kō-ə-'les-ᵊn(t)s\ *n.*
EARTH SCIENCE. The combining or growing together of droplets or small particles of like materials.

Droplets of water vapor in a cloud increase in size by COALESCENCE *until their weight is great enough to cause them to fall as raindrops.*

coal sack \'kōl 'sak\
ASTRONOMY. A massive cloud of dust or gases that absorbs the light from stars and appears as a black spot in the Milky Way.

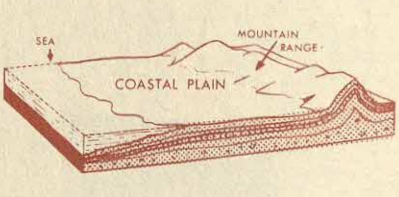
One COAL SACK, *visible from the Northern Hemisphere, is located near Deneb, and another is located near the Southern Cross.*

coal tar \'kōl 'tär\
CHEMISTRY. A gummy, black substance produced as a by-product when bituminous coal is distilled.

Benzene and phenol are two important chemicals obtained from derivatives of COAL TAR.

coastal plain \'kōst-ᵊl 'plān\
EARTH SCIENCE. A plain having one margin on the shore of a sea or other large body of water and extending inland to another margin where there is a marked change in elevation.

A COASTAL PLAIN *generally represents a land area once covered by the sea.*



COASTAL PLAIN

coast ranges \'kōst 'rānj-əz\
EARTH SCIENCE. A mountain system that is nearly parallel to a continental margin; also, a system of folded and faulted mountains near the sea coast; specifically, the mountain ranges along the western coast of North America.

In the western United States, the COAST RANGES *rise steeply from the Pacific Ocean to heights of over 8,000 feet.*

coaxial cable \(') kō-'ak-sē-əl 'kā-bəl\
ENGINEERING. A cylindrical metal sheath surrounding a thin

center core of insulated wires used to transmit such electrical impulses as television and radio signals.

One COAXIAL CABLE *may carry many different electrical impulses simultaneously.*

COCCUS

cobalt \'kō-ˌbȯlt\ *n.*

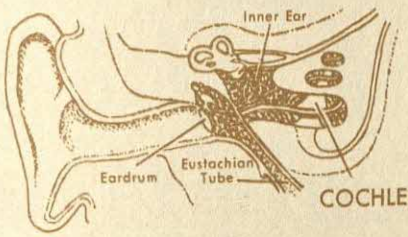
CHEMISTRY. A hard, magnetic, metallic element having a faintly pink color and found in compound form, usually with copper, sulfur and arsenic. Symbol, Co; atomic number, 27; atomic weight, 58.933.

COBALT *is used in the production of alloy steels.*

cobalt 60 \'kō-ˌbȯlt\

CHEMISTRY. A radioisotope produced when cobalt is bombarded by slow neutrons in a reactor, causing radiation that consists of beta particles and gamma rays.

COBALT 60 *is sometimes used in place of X rays or radium in the treatment of cancer.*



COCHLEA

coccus \'käk-əs\ *n.*

BIOLOGY and MEDICINE. A spherically-shaped bacterium.

Some forms of pneumonia are caused by certain species of COCCUS.

cochlea \'käk-lē-ə\ *n.*

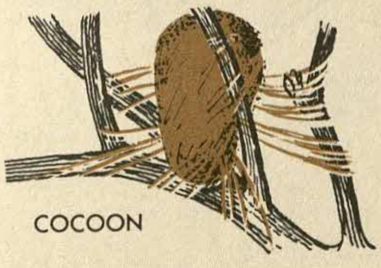
ANATOMY. The spirally-wound tube in the inner ear that contains a fluid, a membrane and the auditory nerve endings.

The primary sense organs of hearing are stimulated by sound vibrations in the fluid contained by the COCHLEA.

cocoon \kə-'kün\ *n.*

ZOOLOGY. An outer covering spun by the larva of some insects prior to the resting, or pupa, stage; also, the egg case of spiders and earthworms.

The COCOON *spun by the silkworm is the source of silk used in clothing.*



COCOON

code \'kōd\ *n.*

ENGINEERING and MATHEMATICS. Any system of symbols that represents data fed to, or produced by, a computer.

One type of CODE, *when fed to a computer, tells the computer what type of operation to perform.*

coefficient \ˌkō-ə-ˈfish-ənt\ *n.*

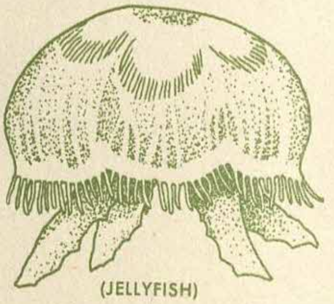
1. MATHEMATICS. Generally, the numerical part of an algebraic term; also, any factor or factors of a given term considered with respect to the other factor or set of factors of that term. 2. PHYSICS. A numerical constant used to multiply a variable quantity in order to calculate the size of a given property, such as the coefficient of friction.

The COEFFICIENT *of the term* $2(x + y)$ *is 2.*

coefficient of linear expansion \ˌkō-ə-ˈfish-ənt əv ˈlin-ē-ər ik-ˈspan-chən\

PHYSICS. The increase in the length of a body per degree rise of its temperature per unit of length. It is expressed as a ratio.

Engineers must know the COEFFICIENT OF LINEAR EXPANSION *of metals used in bridge and building construction.*



(JELLYFISH)

COELENTERATE

coefficient of volume expansion \ˌkō-ə-ˈfish-ənt əv ˈväl-yəm ik-ˈspan-chən\

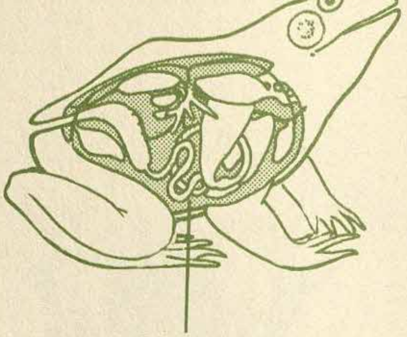
PHYSICS. The increase in the volume of a body per degree rise of its temperature per unit volume. It is expressed as a ratio.

In choosing the metal for an automobile engine piston, an automotive engineer must know the COEFFICIENT OF VOLUME EXPANSION *of each metal being considered.*

coelenterate \si-ˈlent-ə-ˌrāt\ *n.*

ZOOLOGY. One of a group of animals characterized by a digestive cavity with a single opening, by sting cells and by a body form that is radially symmetrical.

The jellyfish is a typical COELENTERATE.



COELOM

coelom \ˈsē-ləm\ *n.*

ANATOMY and ZOOLOGY. In most multicellular animals, the body cavity and its membranous lining, containing such vital organs as the heart and the lungs; also, the embryonic cavity in most animals that develops into the main cavities of the body.

In vertebrates, the COELOM *is divided into the abdominal cavity and the thoracic cavity.*

coenzyme \(ˈ)kō-ˈen-ˌzīm\ *n.*

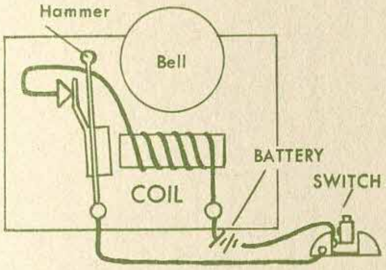
BIOLOGY. The nonprotein fraction of an enzyme necessary for the activation of the enzyme.

Once separated, neither the COENZYME *nor the protein fraction acts as a catalyst.*

cohesion \kō-'hē-zhən\ *n.*

PHYSICS. The intermolecular attraction that binds similar particles together.

COHESION *is very strong in solids, less strong in liquids and very weak in gases.*



coil \'kȯi(ə)l\ *n.*

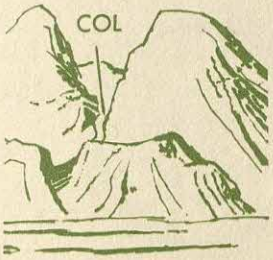
PHYSICS. A wire wound in spiral form and used in an electrical circuit to provide electromagnetic properties.

The electromagnet in an electric doorbell has a COIL.

coke \'kōk\ *n.*

CHEMISTRY. A porous, solid residue resulting from the incomplete combustion of coal heated in a closed chamber, or oven, with a limited supply of air.

COKE *is largely carbon and is a desirable fuel in certain metallurgical industries.*



col \'käl\ *n.*

EARTH SCIENCE. A gap or pass between two mountain peaks or across a ridge.

A COL *is formed by the erosion accompanying the movement of a mountain glacier from its source.*

cold air mass \'kōld 'a(ə)r 'mas\

EARTH SCIENCE. A large body of air that is colder than the surface over which it is moving. It originates as arctic or polar air, and its movement in the Northern Hemisphere is to the southeast and east.

Cool temperatures and clear skies usually accompany a COLD AIR MASS.

COLD-BLOODED

cold-blooded \'kōl(d)-'bləd-əd\ *adj.*

ZOOLOGY. Relating to the body temperature of fish, amphibians and reptiles, whose body temperatures vary according to the temperature of the environment.

The frog, a COLD-BLOODED *animal, has a body temperature approximately the same as that of the water or air in which it lives.*

cold front \'kōld 'frənt\

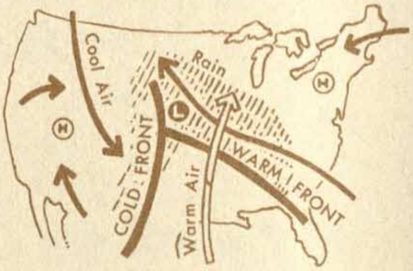
EARTH SCIENCE. The boundary line between a cold air mass and a warm air mass, when the cold air mass is moving toward and pushing under the warm air mass. The term is sometimes limited to the line on the earth's surface where advancing cold air meets a mass of warm air.

The passing of a COLD FRONT *is usually indicated by an increase in pressure, a decrease in temperature and a change in wind direction.*

colliding galaxies \kə-'līd-iŋ 'gal-ək-sēz\

ASTRONOMY. Two large systems of stars that are passing through each other.

The stars within COLLIDING GALAXIES *are still so far apart that there is little chance they will actually hit one another.*



COLD FRONT

collimator \'käl-ə-ˌmāt-ər\ *n.*

PHYSICS. A device for producing parallel beams of such radiations as light or electrons.

In a common form of COLLIMATOR, *a small source of light, such as a pinhole or slit, is placed at the principal focus of the lens.*

collinear \kə-'lin-ē-ər\ *adj.*

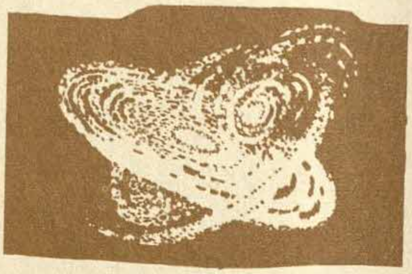
MATHEMATICS. Referring to positions lying on a common line.

Three or more points that are on the same straight line are COLLINEAR.

colloid \'käl-ˌȯid\ *n.*

CHEMISTRY and PHYSICS. A system consisting of two states of matter, one state having particles of very small size, or colloidal particles, and the other state acting as a dispersing medium in which the colloidal particles are suspended; for example, smoke that consists of very fine, solid particles of ash suspended in the dispersing medium, air; see *colloidal size.*

A COLLOID *may be any combination of particles (solid, liquid or gas) of colloidal size dispersed in a medium of any of the three states of matter (solid, liquid or gas), except that a dispersion of a gas in another gas is a true solution.*



COLLIDING GALAXIES

colloidal size \kə-'lȯid-ᵊl 'sīz\

CHEMISTRY and PHYSICS. Having or consisting of particles with diameters ranging from 10 angstroms to 2,000 angstroms.

Particles of COLLOIDAL SIZE *can pass through a filter paper but not through an animal membrane.*

cologarithm \(')kō-'lȯg-ə-ˌrit͟h-əm\ *n.*

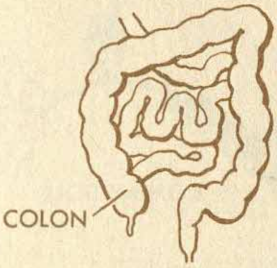
MATHEMATICS. The logarithm of the reciprocal of a number or the negative of the logarithm of the number.

The COLOGARITHM *of 24 equals the logarithm of 1/24, or log 1 — log 24.*

colon \'kō-lən\ *n.*

ANATOMY. The main part of the large intestine, extending from the cecum to the rectum.

The final process of digestion takes place within the COLON.



colony \'käl-ə-nē\ *n.*

1. ZOOLOGY. A group of animals, such as insects or seals, living together and functioning as a community. 2. BIOLOGY. A grouping of bacteria arising from a single cell that reproduces on a culture medium; generally, a group of microorganisms.

Ants live in a highly-organized social COLONY.

color blindness \'kəl-ər 'blīn(d)-nəs\

PHYSIOLOGY. Defective color vision caused by imperfections in the cones of the retina; usually, an inability to distinguish between red and green.

In some extreme cases of COLOR BLINDNESS, *all colors appear gray.*

colorimeter \ˌkəl-ə-'rim-ət-ər\ *n.*

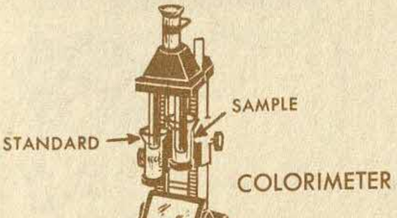
1. CHEMISTRY. An instrument used to identify an unknown component of a liquid or to make a quantitative estimate of the amount of a given substance known to be present in a liquid. Its operation is based on a comparison of the color of the unknown substance or of the unknown value with the color of a known sample used as a standard. 2. PHYSICS. An instrument used to compare or analyze colors by spectral lines; also, a device using colored light filters and photoelectric cells; see *spectrometer.*

The COLORIMETER *is a useful instrument in analytical chemistry.*

coma \'kō-mə\ *n.*

1. MEDICINE. A condition in which there is a lack of sensation or feeling; unconsciousness. 2. ASTRONOMY. A luminous envelope around the nucleus of a comet. 3. PHYSICS. The distortion of light by the rounded surfaces of a lens as these surfaces affect the light from points not on the optical axis. 4. BOTANY. A cluster or tuft, as of hairs on certain seeds.

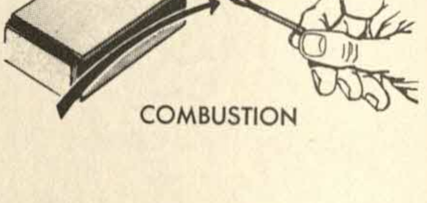
A COMA *may occur in advanced diabetes.*



combining weight \kəm-'bīn-iŋ 'wāt\

CHEMISTRY. A property of an element by which its ratio in a compound is determined; for an element in a given compound, the atomic weight of the element divided by its valence in that compound; the weight of an element that combines with one atomic weight of hydrogen or one-half of an atomic weight of oxygen; the equivalent weight.

An understanding of the basis for a COMBINING WEIGHT *depends upon an understanding of atomic weight, atomic structure and Avogadro's number.*



COMBUSTION

combustion \kəm-'bəs-chən\ *n.*

CHEMISTRY. The chemical reaction of a substance that is oxidized by an oxidizing agent, the reaction being accompanied by the production of heat and light.

The heat produced by the friction between the tip of a match and the surface against which it is struck must be great enough to start COMBUSTION.

comet \'käm-ət\ *n.*

ASTRONOMY. A celestial body that usually consists of a head, composed of a nucleus and coma, and a tail. A comet travels around the sun in an elliptical orbit, and, as it approaches perihelion, its tail points away from the sun.

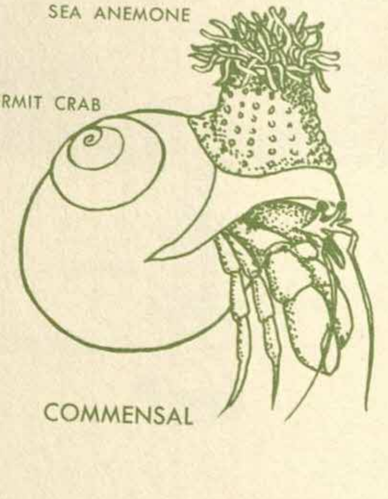
Halley's COMET, *like many other comets, was named after its discoverer.*

COMET

commensal \kə-'men(t)-səl\ *adj.*

BIOLOGY. Referring to an organism that lives in close relationship with another kind of organism and obtains food, shelter or protection from the second without either benefiting or harming it.

The sea anemone is a COMMENSAL *animal that attaches itself to the shell of the hermit crab.*



COMMENSAL

common divisor \'käm-ən də-'vī-zər\

MATHEMATICS. A number or expression that divides evenly each of two or more different quantities or that is a factor of each of these quantities.

A COMMON DIVISOR *of 8, 32 and 64 is 8.*

common factor \'käm-ən 'fak-tər\

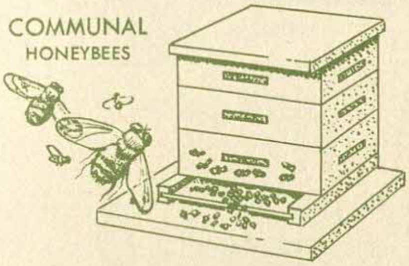
MATHEMATICS. A common divisor.

X is a COMMON FACTOR *of* $x^3 + 2x^2y + xy^2$.

common-ion effect \'käm-ən 'ī-ən i-'fekt\

CHEMISTRY. The effect produced in a solution of an ionized compound when another compound containing ions of the same kind as one of those already in solution is introduced. The volume remains constant, and the effect reduces the concentration of the other ions already in solution.

The COMMON-ION EFFECT *is produced when gaseous hydrogen chloride is bubbled through a concentrated solution of sodium chloride, thus introducing the common ion, chloride (Cl^-), and causing sodium chloride ($NaCl$) to be precipitated, thereby reducing the concentration of the sodium ion (Na^+).*



COMMUNAL HONEYBEES

common multiple \'käm-ən 'məl-tə-pəl\

MATHEMATICS. A number or expression that is exactly divisible by two or more numbers or quantities.

The expression $x^2 - y^2$ *is a* COMMON MULTIPLE *of* $x - y$ *and* $x + y$.

communal \kə-'myün-ᵊl\ *adj.*

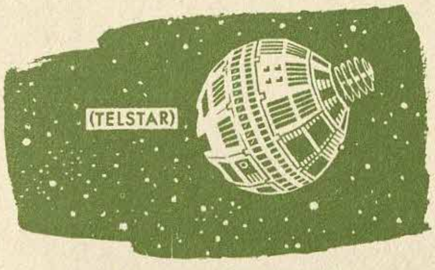
BIOLOGY. Referring to an association of certain animals that live together, with each member performing specific tasks.

Honeybees, with a division of labor among the queen, drones and workers, exhibit a form of COMMUNAL *life.*

communicable disease \kə-'myü-ni-kə-bəl diz-'ēz\

MEDICINE. An infectious disease that can be passed from one organism to another, either directly or indirectly.

Hospital wards are set up to prevent the spread of any COMMUNICABLE DISEASE.



COMMUNICATIONS SATELLITE

communications satellite \kə-ˌmyü-nə-'kā-shənz 'sat-ᵊl-ˌīt\

ASTRONAUTICS. A satellite that is used as a relay station for radio and television signals either by reflection (passive satellite) or by reception, amplification and transmission (active satellite).

The United States' COMMUNICATIONS SATELLITE, *Telstar, made possible the first live telecasts between Europe and North America.*

commutative law \'käm-yə-ˌtāt-iv 'lȯ\

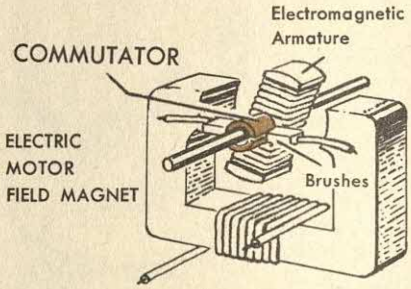
MATHEMATICS. A principle stating that the result obtained by combining two elements under a given operation is independent of the order in which the elements are combined. Thus, addition and multiplication of real numbers are commutative, while subtraction and division are not.

By the COMMUTATIVE LAW, $a + b = b + a$ *and* $a \times b = b \times a$.

commutator \ˈkäm-yə-ˌtāt-ər\ *n.*

ENGINEERING. In a direct current generator, a device for transmitting the reversing current produced in the armature and delivering it to the conductors as direct current; also, in a direct current motor, a device (split ring) reversing the current entering the coils of the armature; also, in an alternating current generator, a cylindrical ring assembly (slip ring) delivering the current produced to the collecting brushes.

Depending on the type of COMMUTATOR *used, a generator will supply either direct or alternating current.*



companion cells \kəm-ˈpan-yən ˈselz\

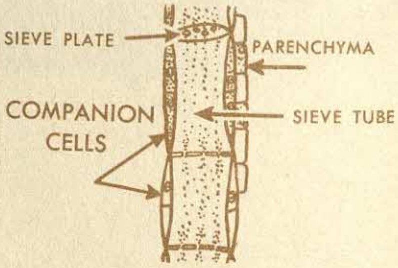
BOTANY. In seed plants, the long and narrow, thin-walled cells that lie next to the sieve tubes and that are believed to be closely associated with them in function.

Downward conduction of dissolved materials occurs through the sieve tubes and possibly through the parenchyma cells and the COMPANION CELLS.

comparative anatomy \kəm-ˈpar-ət-iv ə-ˈnat-ə-mē\

ANATOMY and ZOOLOGY. The study of the structures of various kinds of animals, particularly with respect to their likenesses and differences.

The study of COMPARATIVE ANATOMY *reveals many similarities in the skeletal structures of mammals.*



compass \ˈkəm-pəs\ *n.*

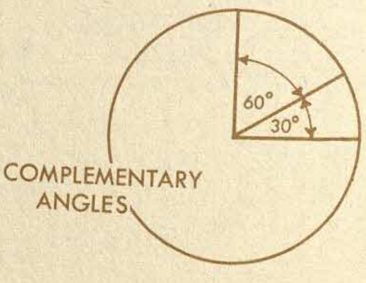
1. EARTH SCIENCE. An instrument used to determine direction; usually a magnetic compass consisting of a magnetic needle supported at its center of gravity and free to turn under the influence of the earth's magnetic field. 2. MATHEMATICS. An instrument used for drawing circles or arcs of circles and to duplicate or determine the distance between two points; often plural, as a pair of compasses.

A gryocompass is a special kind of nonmagnetic COMPASS *that makes use of the motion of a gyroscope to indicate direction.*

complementary angles \ˌkäm-plə-ˈment-ə-rē ˈaŋ-gəlz\

MATHEMATICS. Two angles whose sum is that of a right angle, or 90 degrees.

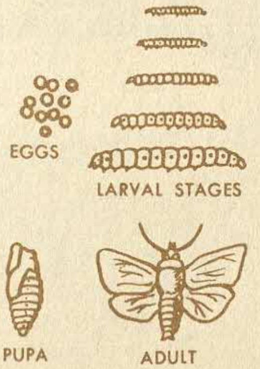
The two acute angles of any right triangle are COMPLEMENTARY ANGLES.



complementary color \ˌkäm-plə-ˈment-ə-rē ˈkəl-ər\

PHYSICS. One of two colors of light that will produce white when suitable proportions of the two are mixed; also, one of two pigment colors that will produce gray when suitable proportions of the two are mixed.

Yellow is a COMPLEMENTARY COLOR *of purple-blue.*



COMPLETE METAMORPHOSIS
(OF MOTH)

complete metamorphosis \kəm-'plēt ˌmet-ə-'mȯr-fə-səs\
ZOOLOGY. A type of metamorphosis in which the developing organism passes through four stages: egg, larva, pupa and adult; see *incomplete metamorphosis.*

Butterflies and moths undergo COMPLETE METAMORPHOSIS *during their life cycles.*

complex fraction \käm-'pleks 'frak-shən\
MATHEMATICS. A fraction that has a fraction in its numerator or denominator, or in both numerator and denominator.

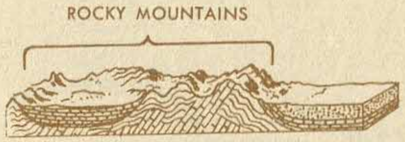
The fraction $\frac{2\,3/8}{9\,5/6}$ *is a* COMPLEX FRACTION.

complex ion \käm-'pleks 'ī-ən\
CHEMISTRY. An electrically-charged, relatively-complex radical or group of atoms, such as that formed by the combination of ions and molecules.

The COMPLEX ION $Ni\ (NH_3)_6^{+\ +}$ *is found in a solution of* $NiCl_2 \cdot 6NH_3$.

complex mountains \käm-'pleks 'mau̇nt-ᵊnz\
EARTH SCIENCE. Mountains formed by combinations of folding and faulting, or diastrophism, and volcanic action, or volcanism.

The Rocky Mountains and the Blue Ridge Mountains are COMPLEX MOUNTAINS.



COMPLEX MOUNTAINS

complex number \käm-'pleks 'nəm-bər\
MATHEMATICS. Any real or imaginary number with the general form $a + ib$, in which a and b are the real parts and i is the imaginary part equal to $\sqrt{-1}$.

To add one COMPLEX NUMBER *to another, the real parts and the imaginary parts must be summed separately; for example,* $(3 + 4i) + (5 - i) = (3 + 5) + (4i - i) = 8 + 3i$.

complex salt \käm-'pleks 'sȯlt\
CHEMISTRY. A salt that, in solution, gives at least one kind of complex ion.

$Zn(CN)_2 \cdot 2KCN$ *is classified as a* COMPLEX SALT *because it gives a complex ion,* $Zn(CN)^{--}$*, when dissolved.*

component \kəm-'pō-nənt\ *n.*

CHEMISTRY. One of the ingredients in a chemical mixture or compound.

Copper is one COMPONENT *of the alloy brass.*

composite cone \käm-'päz-ət 'kōn\

EARTH SCIENCE. A volcanic cone consisting of interbedded lava flows and cinders. A composite cone has a steep slope of about 70 degrees at the summit, gradually decreasing to about a 5-degree slope at the base.

Mount Rainier in the United States is an example of a COMPOSITE CONE.

COMPOSITE CONE

composition \ˌkäm-pə-'zish-ən\ *n.*

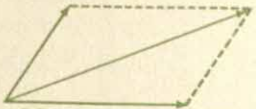
CHEMISTRY. The component parts or elements in a compound, given in relative numbers of atoms or as percentages of weight.

The atomic COMPOSITION *of hematite, Fe_2O_3, is two atoms of iron to three atoms of oxygen.*

composition of forces \ˌkäm-pə-'zish-ən əv 'fō(ə)rs-əz\

PHYSICS. In mechanics, the determination of the resultant of two or more forces acting on a body.

In a parallelogram representative of two forces acting on a body, a diagonal represents the force resulting from the COMPOSITION OF FORCES *and indicates both the direction and amount of the force.*



COMPOSITION OF FORCES

compound \'käm-ˌpaund\ *n.*

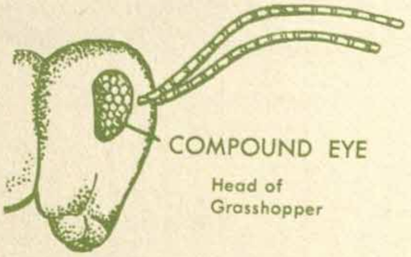
CHEMISTRY. A substance homogeneous in nature and pure in quality, consisting of two or more elements in chemical combination, with physical and chemical properties different from those of the elements of which it is composed.

Sugar is a COMPOUND *of carbon, hydrogen and oxygen in chemical combination.*

compound eye \'käm-ˌpaund 'ī\

ZOOLOGY. In insects and crustaceans, an eye composed of numerous lenses or facets containing separate nerve endings.

The large COMPOUND EYE *of a grasshopper projects from the front and sides of its head.*



COMPOUND EYE

Head of Grasshopper

compound fracture \'käm-ˌpaund 'frak-chər\

MEDICINE. A broken bone that penetrates the skin; an open fracture.

A COMPOUND FRACTURE *takes longer to heal than does a simple one.*

compound leaf \'käm-ˌpau̇nd 'lēf\

BOTANY. A leaf whose blade is divided into two or more distinct parts called leaflets.

The strawberry plant has a COMPOUND LEAF.

compound microscope \'käm-ˌpau̇nd 'mī-krə-ˌskōp\

A microscope that has an objective lens to produce an enlarged real image and an ocular lens, or eyepiece, to magnify the image still further by forming a virtual image.

A COMPOUND MICROSCOPE *is usually used when magnifications up to 1,500 diameters are desired.*

STRAWBERRY PLANT

compound number \'käm-ˌpau̇nd 'nəm-bər\

MATHEMATICS. A quantity expressed as a sum of two or more denominations of a given kind of measure.

The measurement 4 yards, 3 feet and 2 inches is a COMPOUND NUMBER.

compression \kəm-'presh-ən\ *n.*

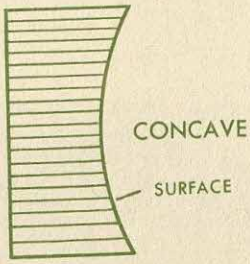
ENGINEERING and PHYSICS. The decrease in volume that occurs when a force acts upon a mass; in practical use, applied particularly to gases; also, the condensation phase of a wave in a gas, liquid or solid as compared with the rarefaction phase.

COMPRESSION *of the gasoline vapor and air mixture in the cylinder of an automobile engine occurs when both the intake and exhaust values are closed.*

compressor \kəm-'pres-ər\ *n.*

ENGINEERING. A mechanical device used to apply pressure to gases.

The supercharger on a gasoline engine is an air COMPRESSOR.



computer \kəm-'pyüt-ər\ *n.*

1. MATHEMATICS. Any instrument that carries out mathematical operations. 2. ENGINEERING. In navigation or gunnery, a device for performing rapid calculations, such as position or range of fire; also, in map making, one who computes such features as longitude or latitude.

A COMPUTER *may solve in seconds a problem that would take months for men to solve.*

concave \kän-'kāv\ *adj.*

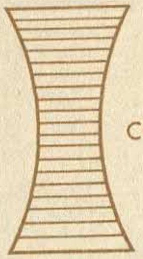
PHYSICS. Having the shape of, or similar to, the interior surface of a hollow ball or the interior of a curved line.

A CONCAVE *mirror can reflect light to a point or focus.*

concavo-concave \kän-ˌkā-(ˌ)vō-kän-ˈkāv\ *adj.*

MATHEMATICS and PHYSICS. Having two opposite surfaces, each of which is concave outward (usually describes a lens).

A CONCAVO-CONCAVE *lens causes light passing through it to spread out.*



CONCAVO-CONCAVE

concavo-convex \kän-ˌkā-(ˌ)vō-kän-ˈveks\ *adj.*

MATHEMATICS and PHYSICS. Referring to a figure, form or device that is concave on one side and convex on the other.

Two concentric circles are CONCAVO-CONVEX *with respect to a line drawn between them.*

conceive \kən-ˈsēv\ *v.*

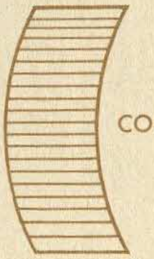
BIOLOGY. To start the growth of a new organism by the fertilization of an egg.

Certain animals, such as mice and hamsters, are able to CONCEIVE *and bear litters several times in one year.*

concentration \ˌkän(t)-sən-ˈtrā-shən\ *n.*

CHEMISTRY. The amount of a dissolved substance present in a given amount of solution.

The CONCENTRATION *of salt in salt water increases when some of the water evaporates.*



CONCAVO–CONVEX

concentric \kən-ˈsen-trik\ *adj.*

MATHEMATICS. Referring to two figures that have a common center.

The inside and outside rims of a wheel are CONCENTRIC *circles.*

conception \kən-ˈsep-shən\ *n.*

BIOLOGY. Fertilization of an egg resulting in the creation, and normally the growth, of a new organism.

The time interval between CONCEPTION *and birth varies among different species of animals.*

conceptual definition \kən-ˈsep-chə(-wə)l ˌdef-ə-ˈnish-ən\

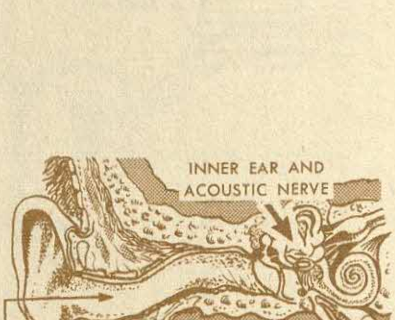
CHEMISTRY and PHYSICS. A description of a substance based on the composition and structure of the substance.

A CONCEPTUAL DEFINITION *attempts to identify the causes of the observed behavior and properties of a substance.*

concha \ˈkäŋ-kə\ *n.*

ANATOMY. Any of several structures of the body that resembles a shell in form, as the largest hollow of the external ear or the turbinate bones of the nasal passage; also, the whole external ear, or pinna.

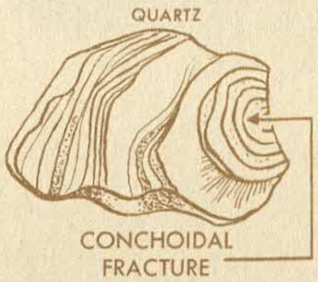
The form of the CONCHA *concentrates sound waves.*



conchoidal fracture \käŋ-ˈkȯid-ᵊl ˈfrak-chər\

EARTH SCIENCE. The manner in which some minerals and rocks break, producing a curved, shell-like surface.

Quartz is a mineral exhibiting CONCHOIDAL FRACTURE.



concrete number \ˈkän-ˌkrēt ˈnəm-bər\

MATHEMATICS. A number or quantity and the specific unit or object with which it is associated.

The expression "15 inches" is a CONCRETE NUMBER.

concretion \kän-ˈkrē-shən\ *n.*

EARTH SCIENCE. A ball-shaped or disk-shaped accumulation of mineral matter in a sedimentary rock.

Common minerals that may be found in a CONCRETION *are calcite, dolomite, silica or limonite.*

condensation \kän-ˌden-ˈsā-shən\ *n.*

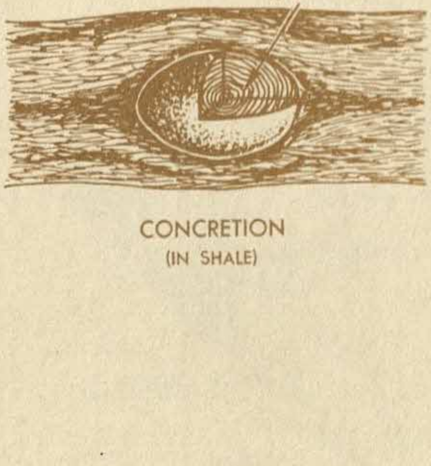
1. PHYSICS. The process by which a gas or vapor is changed into a liquid or solid; also, the resultant liquid or solid. 2. CHEMISTRY. A type of reaction in which small molecules join to form large molecules. Small molecules, such as water, are split off in the reaction.

Dew is the result of the CONDENSATION *of water vapor on cold objects.*

condensation nucleus \ˌkän-ˌden-ˈsā-shən ˈn(y)ü-klē-əs\

EARTH SCIENCE. A small particle forming the center around which water vapor in the air condenses.

A microscopic salt particle in the atmosphere can serve as a CONDENSATION NUCLEUS *in the formation of a raindrop.*



CONCRETION
(IN SHALE)

condensation polymer \kän-ˌden-ˈsā-shən ˈpäl-ə-mər\

CHEMISTRY. A polymer formed from a reaction in which a simple molecule, such as water, is eliminated, and in which monomers join.

The synthetic fabric Dacron is a CONDENSATION POLYMER.

condensed acid \kən-ˈden(t)st ˈas-əd\

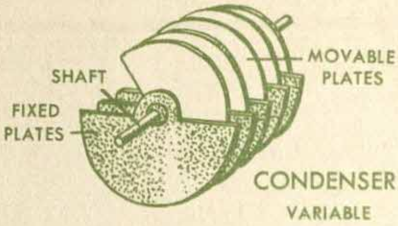
CHEMISTRY. The product that forms when one or more molecules of water split out of one or more acid molecules.

A CONDENSED ACID *frequently has the property of an unsaturated acid.*

condenser \kən-ˈden(t)-sər\ *n.*

1. ENGINEERING. A device or mechanism used to change a vapor, such as steam, into liquid by cooling the vapor. 2. PHYSICS. A device for storing electric charges; see *capacitor.*

In distillation experiments, evaporated vapor is often recovered as a liquid by passing it through a water-cooled CONDENSER.



CONDENSER
VARIABLE

conductance \kən-ˈdək-tən(t)s\ *n.*

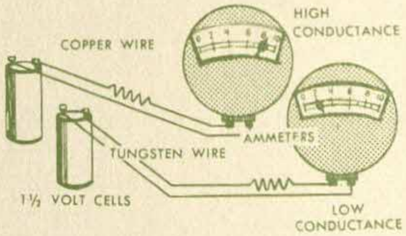
PHYSICS. The property of a substance that causes it to transmit energy, usually electricity.

The CONDUCTANCE *of salt water is greater than that of pure water.*

conduction \kən-ˈdək-shən\ *n.*

PHYSICS. The process by which energy, such as heat, sound or electricity, is transmitted by a medium (solid, liquid or gas), without movement of the medium itself.

Since outer space is a nearly perfect vacuum, no heat reaches the earth from the sun by CONDUCTION.



CONDUCTANCE

cone \ˈkōn\ *n.*

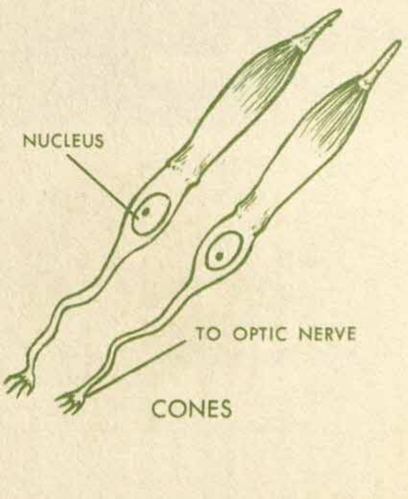
1. MATHEMATICS. In geometry, a solid figure bounded by a closed curve (called the base) in a plane and the surface formed by straight-line segments (called the elements) that connect points on the boundary of the base to a fixed point (called the vertex) outside the plane of the base. 2. EARTH SCIENCE. A peak formed by ejected material from a volcano; also, a steep-sided pile of sand, gravel or boulders deposited at the front edge of a melting glacier. 3. BOTANY. In certain conifers and cycads, a cluster of pollen-bearing or ovula-bearing scales.

A CONE *is called circular if its base is a circle or elliptic if its base is an ellipse.*

cones \ˈkōnz\ *n.*

ANATOMY. The tiny, cone-shaped outer ends of the visual cells in the second of the ten layers comprising the retina of the eye.

The retinal CONES *function as color receptors, but they are much less sensitive to light of low intensity than the rod cells also present in the retina.*



CONES

configuration \kən-ˌfig-(y)ə-ˈrā-shən\ *n.*

CHEMISTRY. The arrangement of electrons in a theoretical model of an atom; also, the geometrical arrangement of atoms in a molecular model.

The CONFIGURATION *of atoms in a molecular model can explain many of the real molecule's properties.*

congenital \kən-'jen-ət-ᵊl\ *adj.*
BIOLOGY. Present from birth, as a deformity or disease.

CONGENITAL *heart disease is a condition that can often be corrected surgically.*

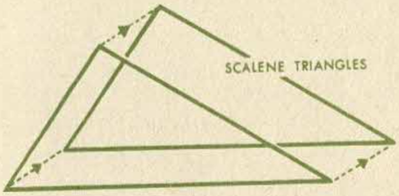
CONGLOMERATE

conglomerate \kən-'gläm-(ə-)rət\ *n.*
EARTH SCIENCE. A sedimentary rock consisting of small, rounded fragments or pebbles cemented together in a matrix of finer material.

The cementing material, or matrix, in a CONGLOMERATE *is usually composed of either silica or clay minerals.*

congruent \kən-'grü-ənt\ *adj.*
MATHEMATICS. Referring to two geometrical figures of the same size and shape whose parts coincide exactly when one figure is placed or superimposed, upon the other.

Two triangles are CONGRUENT *if their corresponding sides are equal, but two triangles are not necessarily congruent if their corresponding angles are equal.*



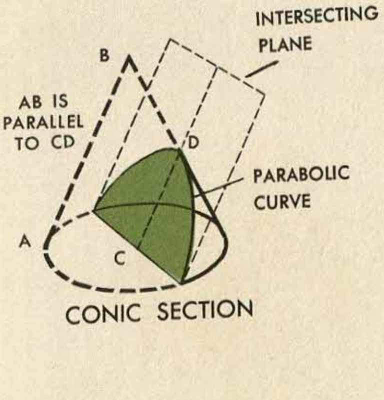
CONGRUENT

conic map projection \'kän-ik 'map prə-'jek-shən\
EARTH SCIENCE. A map produced by projecting a representation of part of the earth's surface onto a cone that is tangent to the surface and then unrolling the cone to form a plane map surface; see *Lambert conformal projection.*

A CONIC MAP PROJECTION *is most accurate at the latitude where the cone touches the globe.*

conic section \'kän-ik 'sek-shən\
MATHEMATICS. A curve formed when a plane cuts or intersects a right circular cone.

A parabola is a CONIC SECTION.



CONIC SECTION

conifer \'kän-ə-fər\ *n.*
BOTANY. A group of gymnosperms bearing cones and usually characterized by needle-shaped leaves. The group includes pines, spruces and firs.

The CONIFER *is a widely-used source of wood pulp and lumber.*

conjugate \'kän-ji-gət\ *adj.*
1. BIOLOGY. Joined in pairs; coupled. 2. MATHEMATICS. Referring to such mathematical forms and expressions as arcs, real and complex numbers and angles or functions that are usually considered in pairs and that have interchangeable properties.

Two CONJUGATE *cells lie side by side in the sexual reproduction of spirogyra.*